First Results from the Kepler Mission

Jason H. Steffen
Fermilab Center for Particle Astrophysics
Fermilab Wine and Cheese Talk
February 12, 2010

Fermilab Exoplanet Team

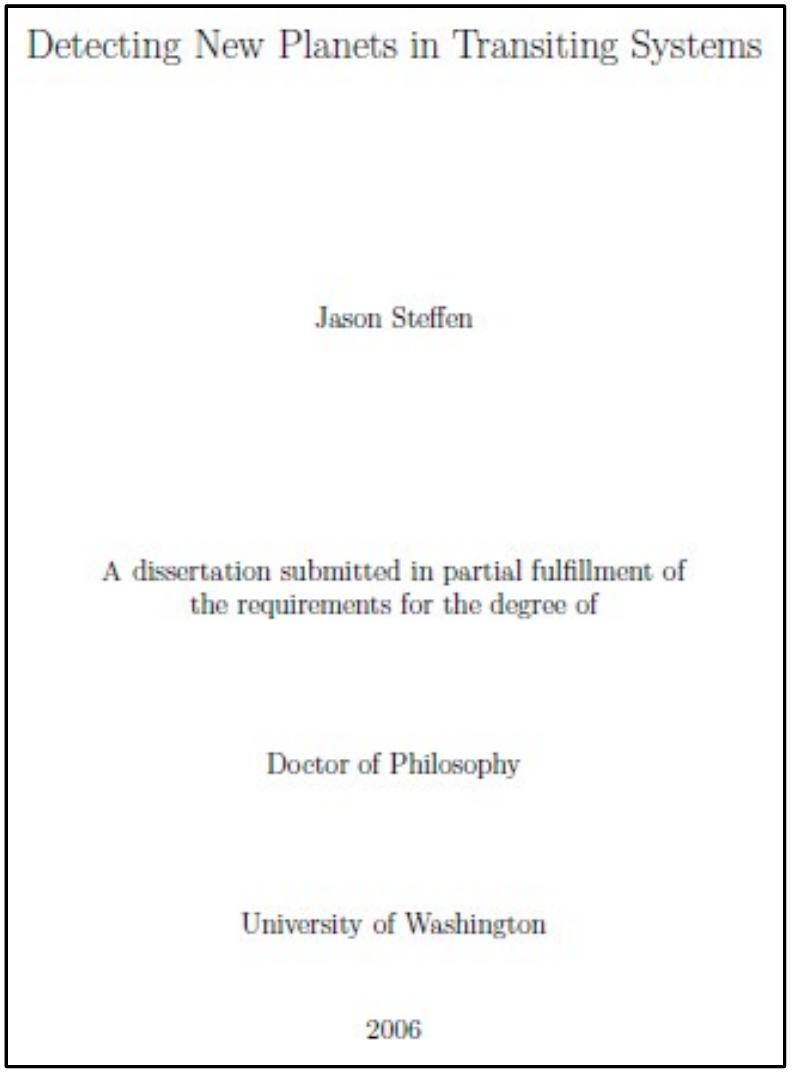
Jason H. Steffen

Fermilab Exoplanet Team

How did you get involved with exoplanets and Kepler?

Fermilab Exoplanet Team

How did you get involved with exoplanets and Kepler?



Detecting New Planets in Transiting Systems

Jason Steffen

A dissertation submitted in partial fulfillment of
the requirements for the degree of

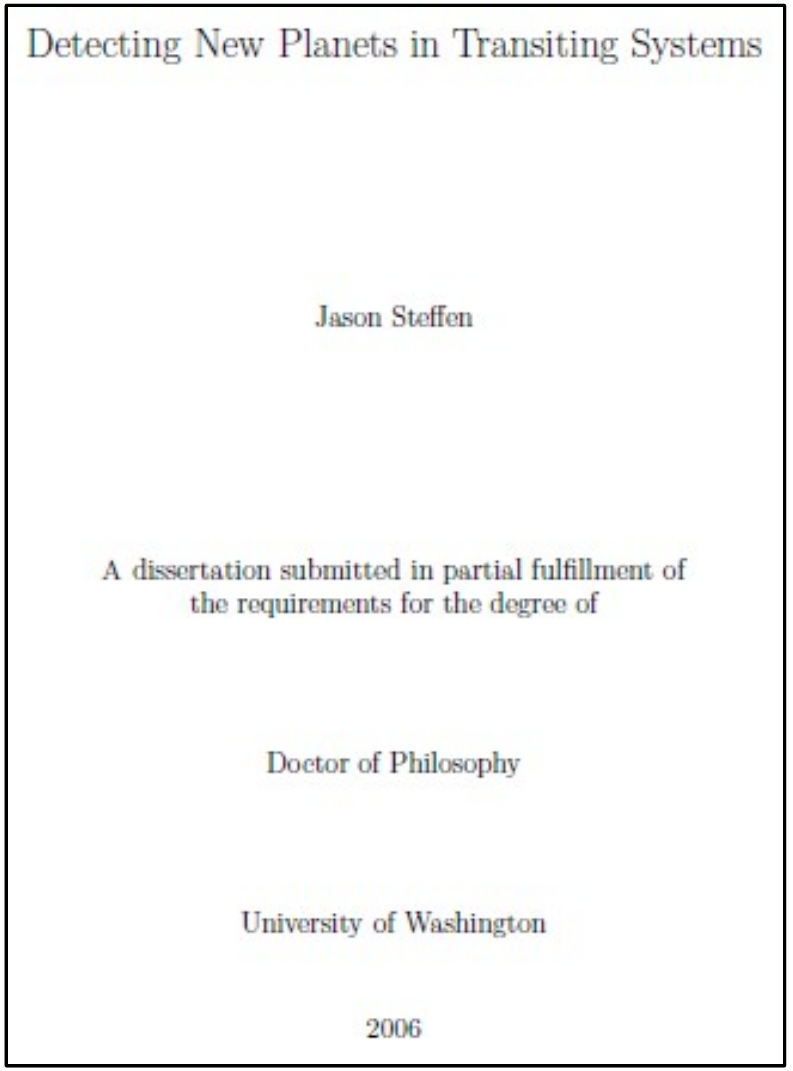
Doctor of Philosophy

University of Washington

2006

Fermilab Exoplanet Team

How did you get involved with exoplanets and Kepler?



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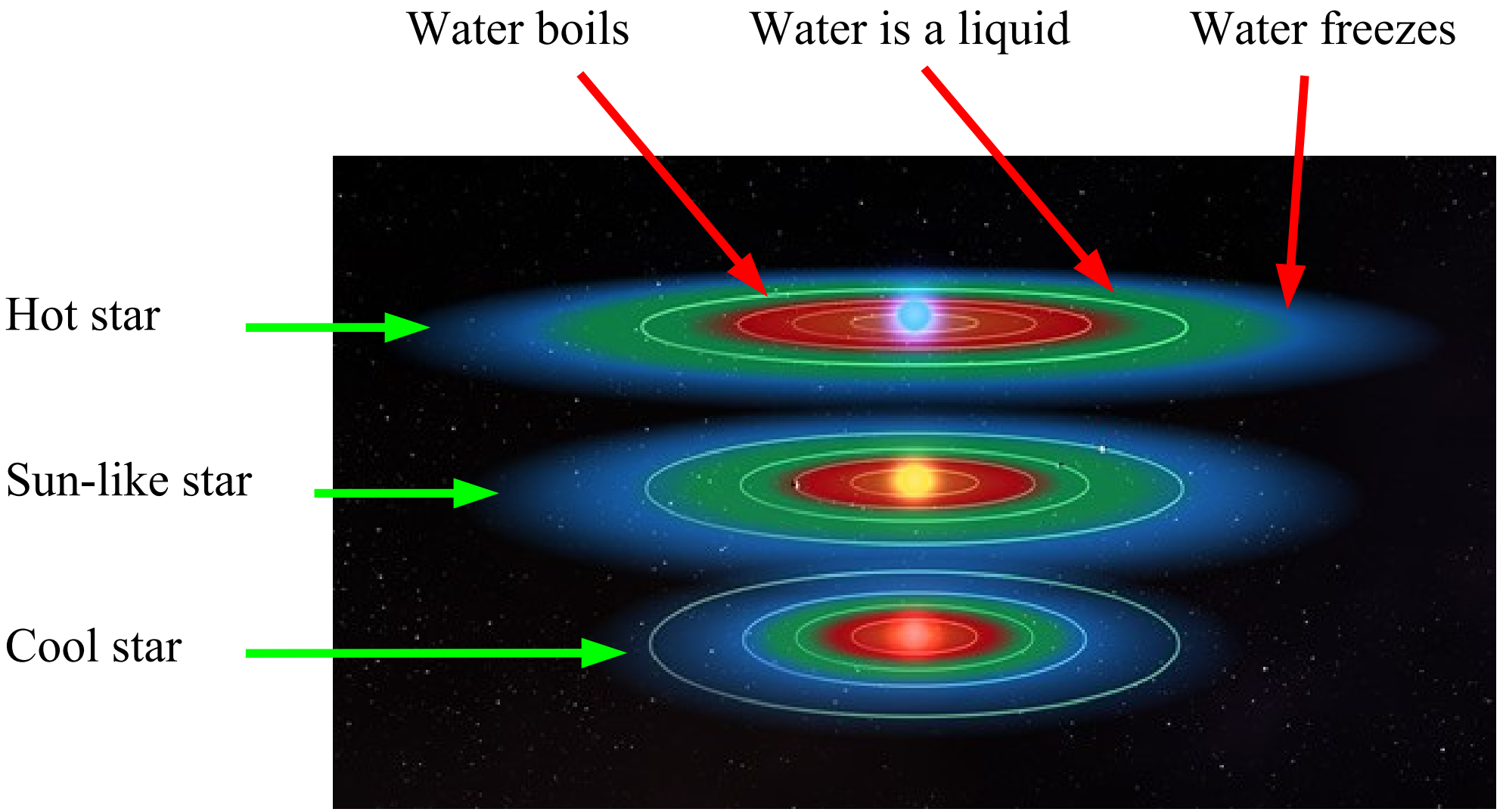
How did you get involved with Fermilab?

Talk Overview

- Motivation for the Kepler mission
- Planet Detection Methods
- Mission overview
  - instrument design
  - survey strategy
  - ground-based program
- Launch and flight operations
- First exoplanet discoveries
- Additional Kepler science
- Future of the mission

Kepler Motivation

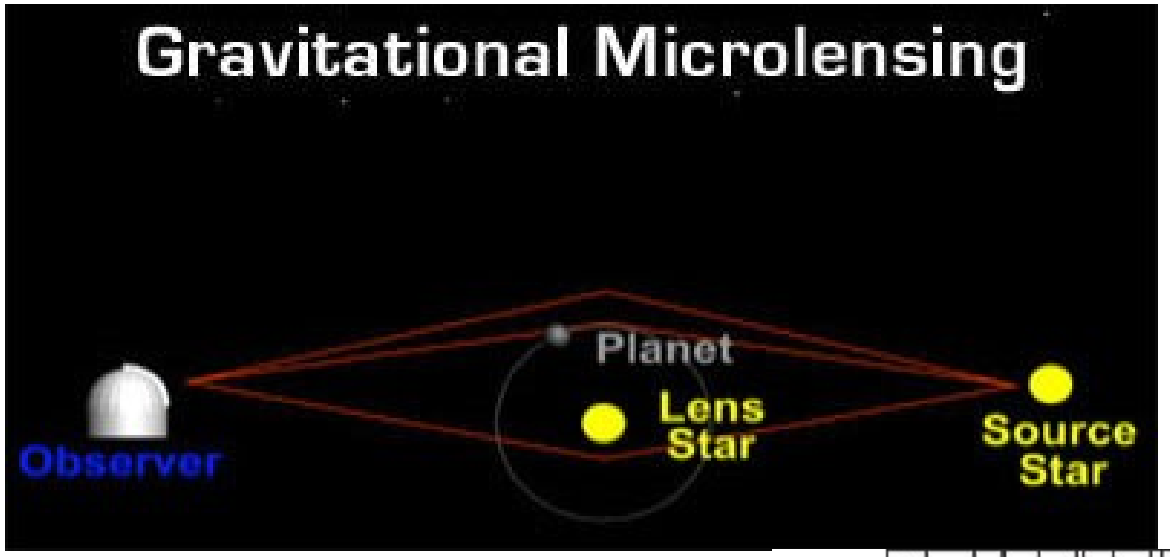
Kepler Motivation



Planet Finding: Pulse Timing

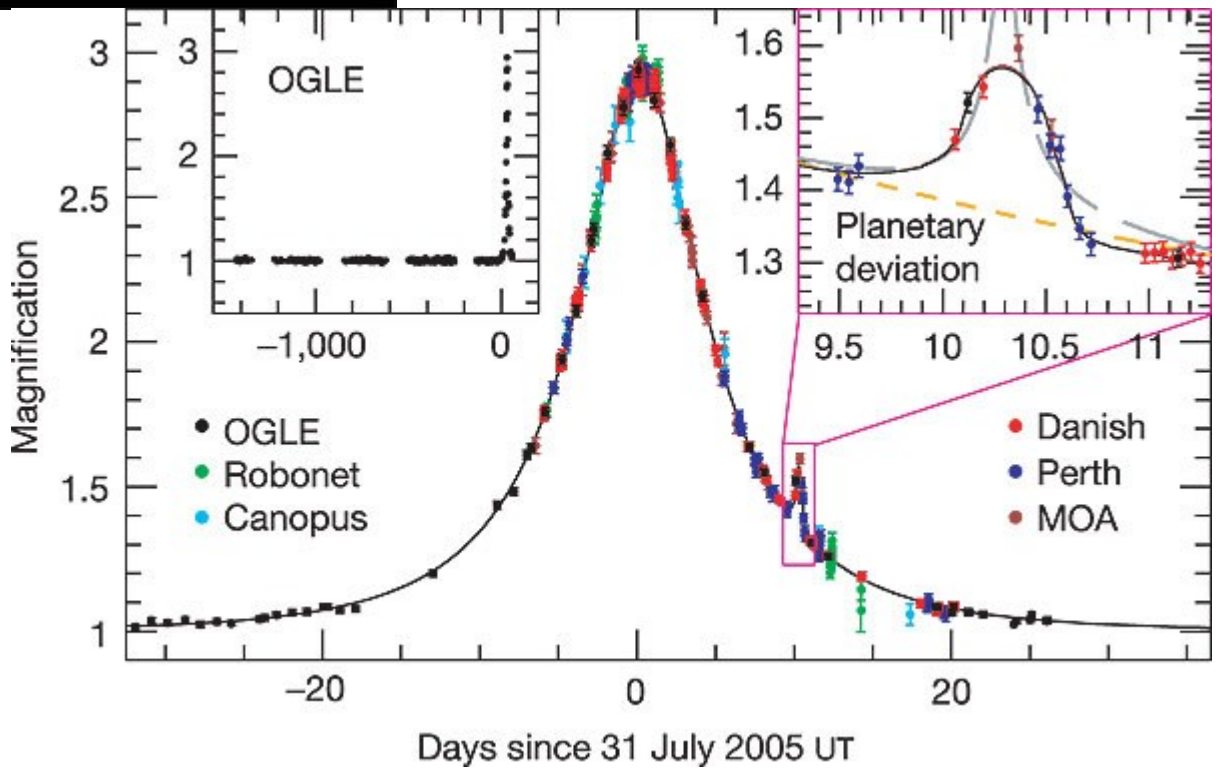
These aren't the planets we're looking for.

Planet Finding: Gravitational Lensing

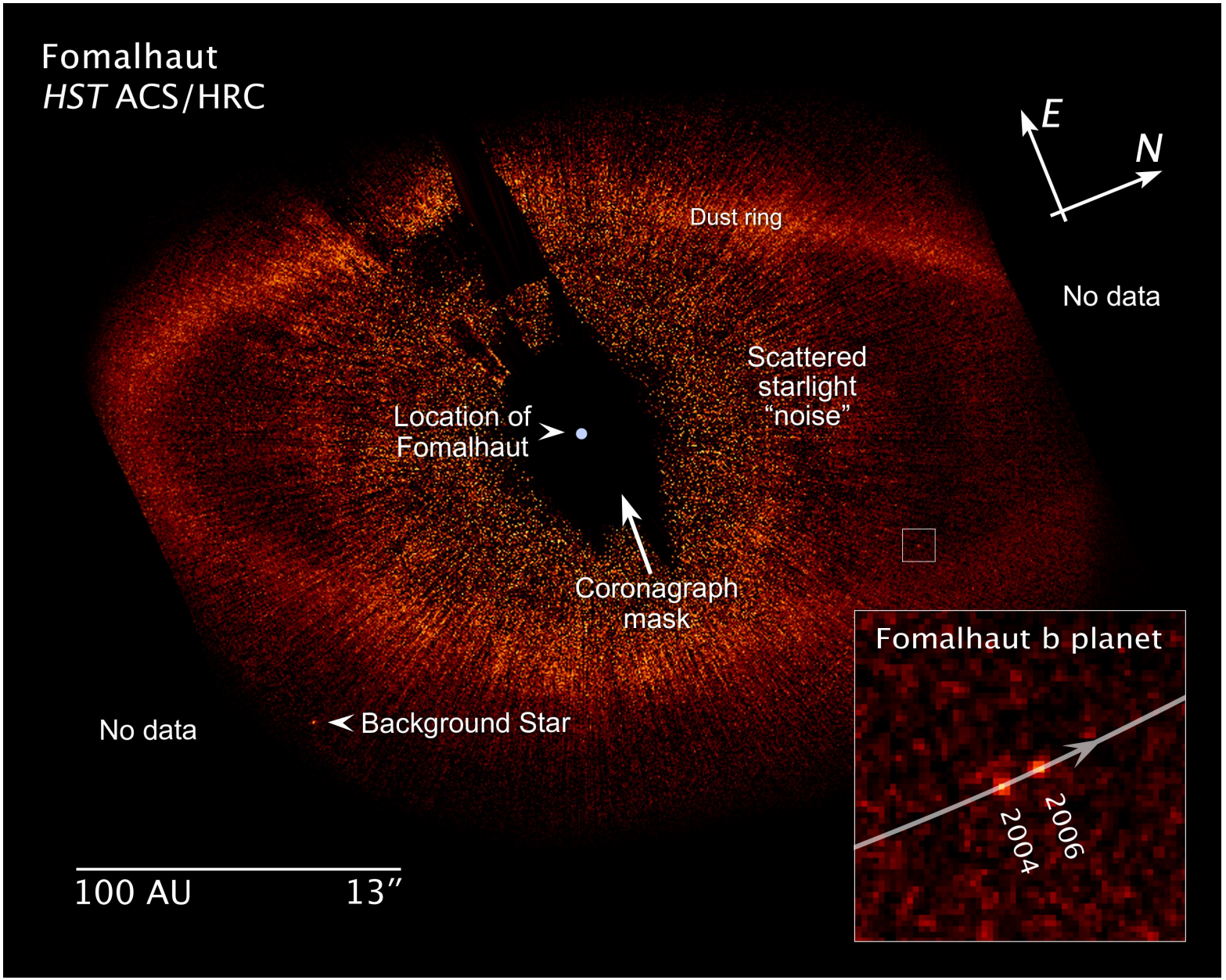


Currently, the only way to get a galaxy-wide census of planets.

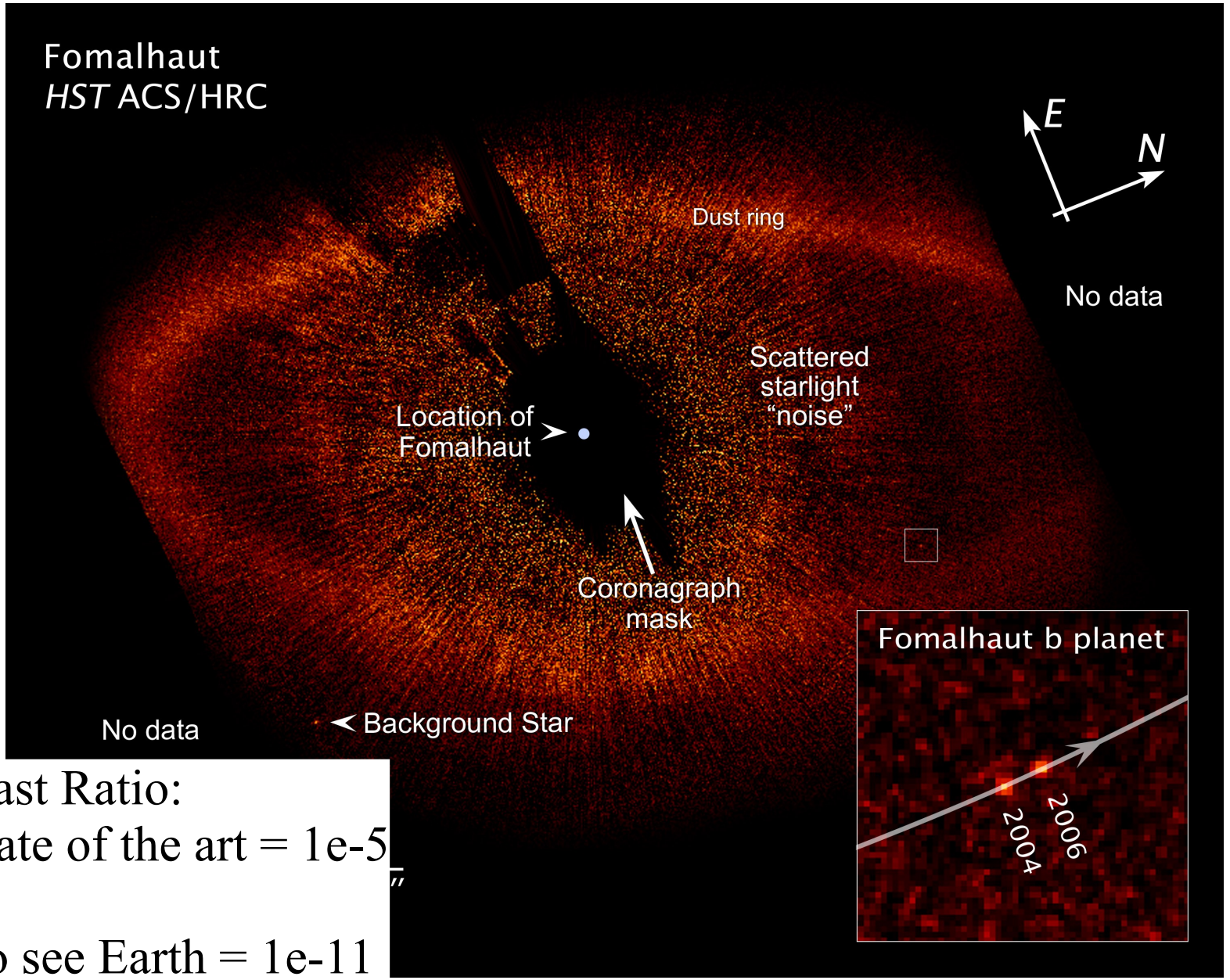
These are planets that you can't see orbiting stars that you can't see.



Planet Finding: Direct Imaging



Planet Finding: Direct Imaging

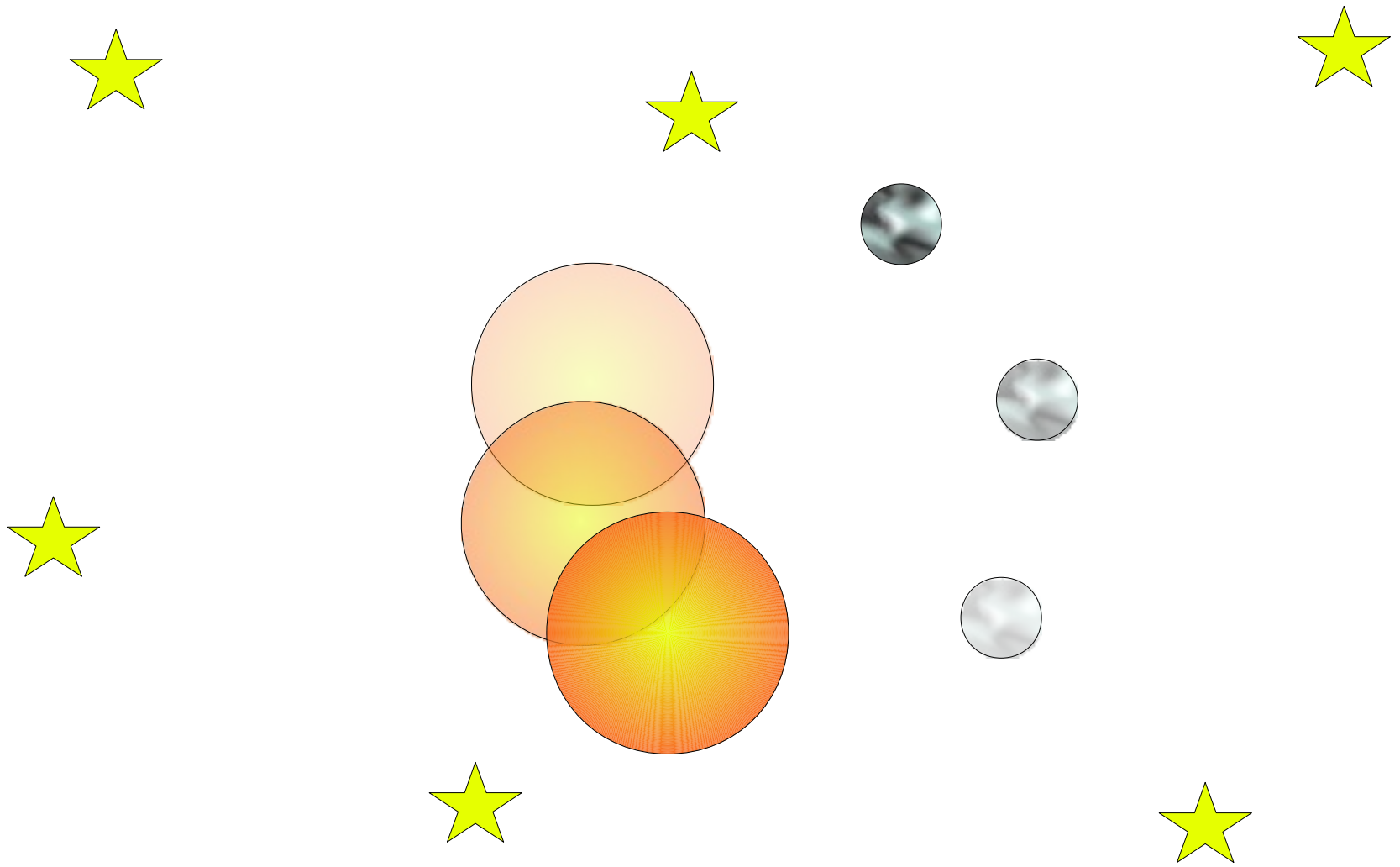


Contrast Ratio:

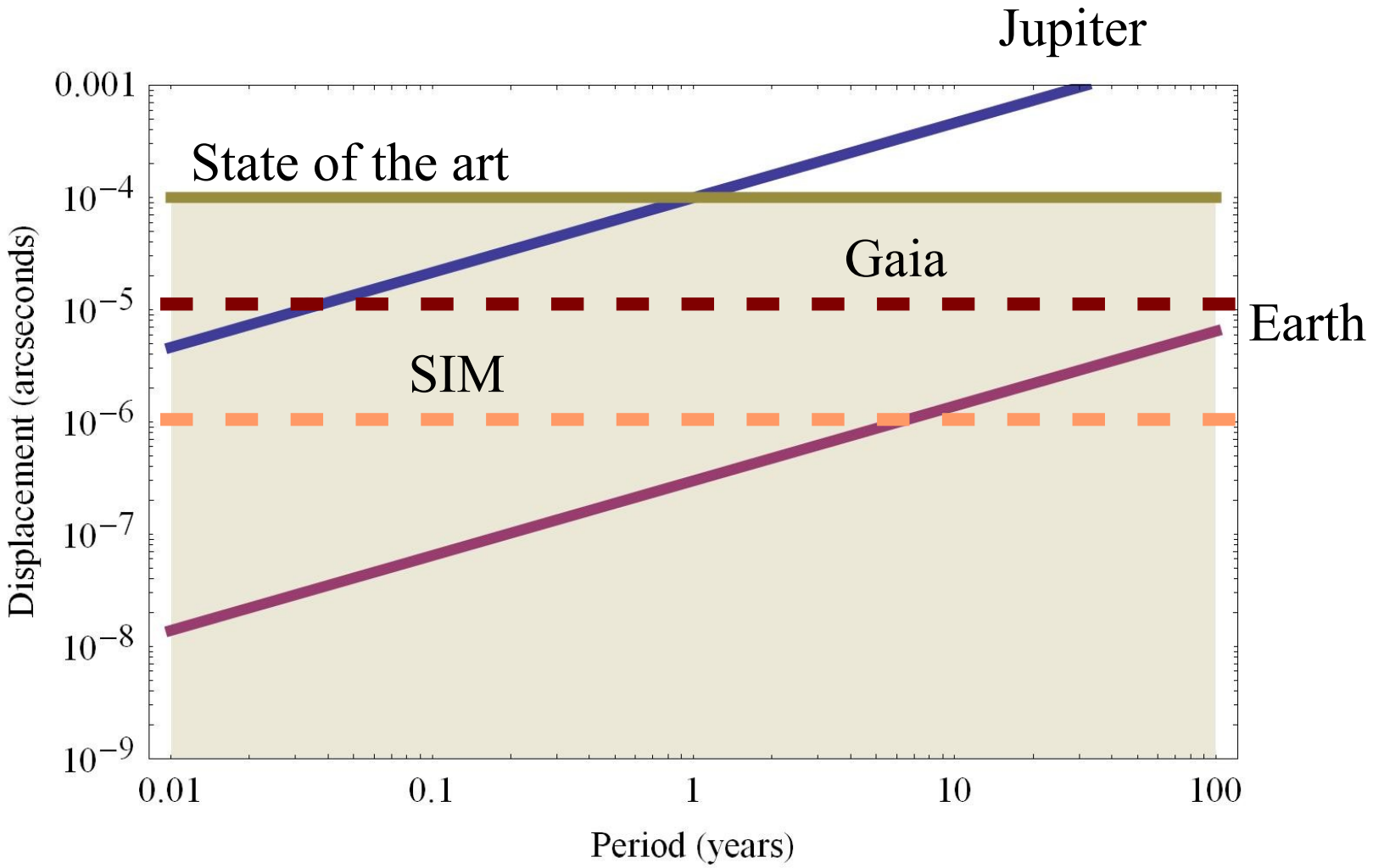
State of the art = 1e-5

To see Earth = 1e-11

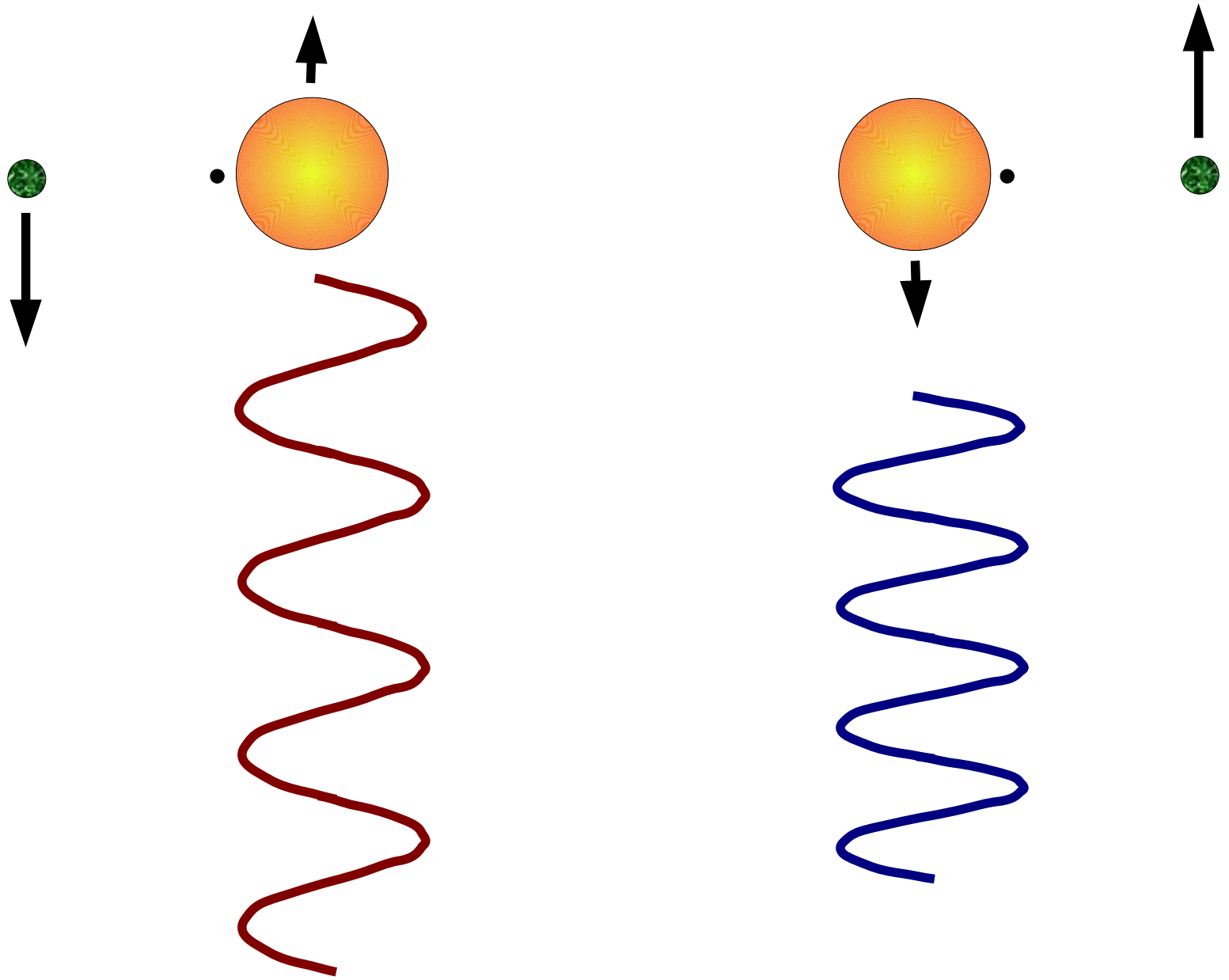
Planet Finding: Astrometry



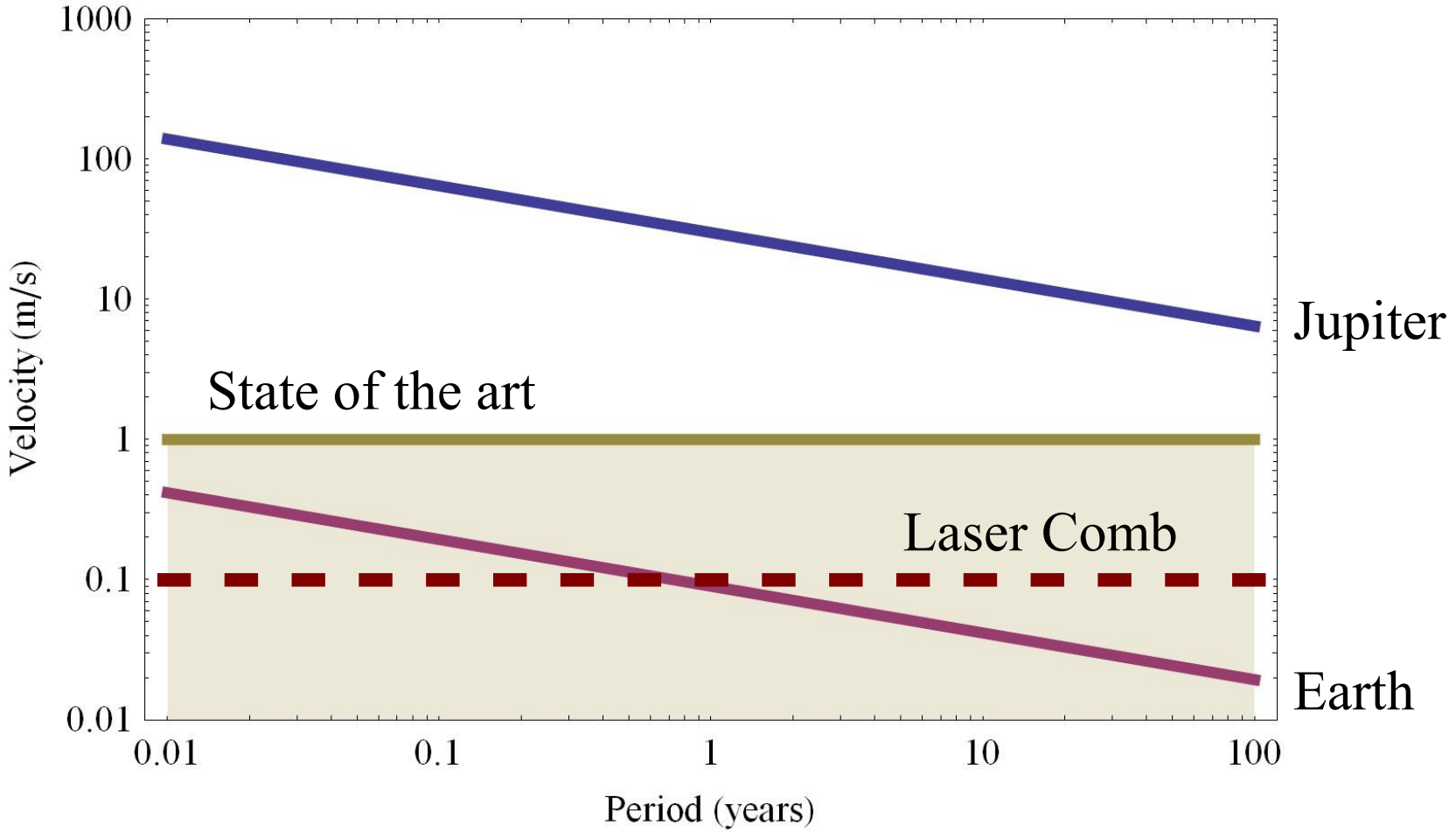
Planet Finding: Astrometry



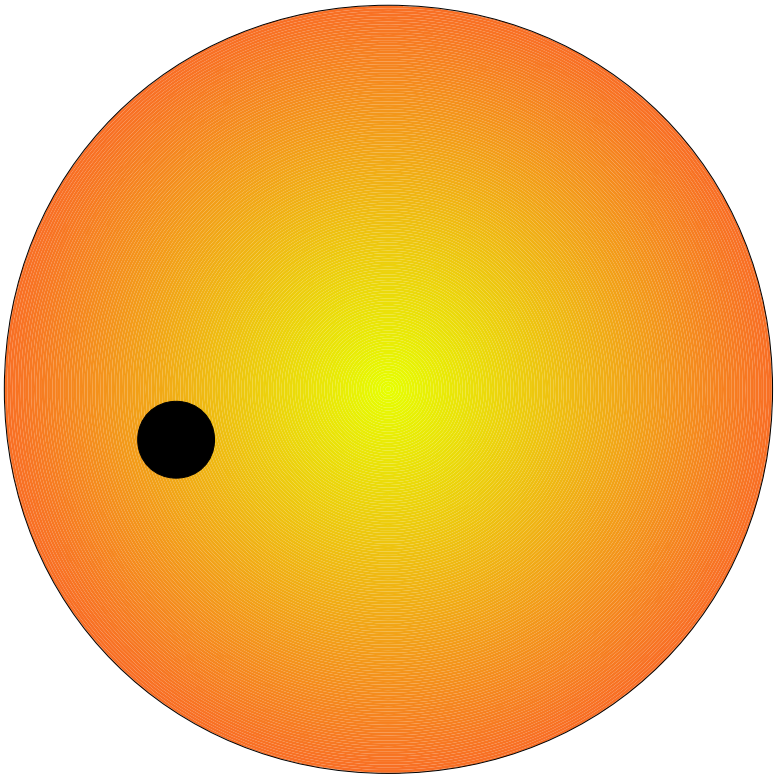
Planet Finding: Radial Velocity

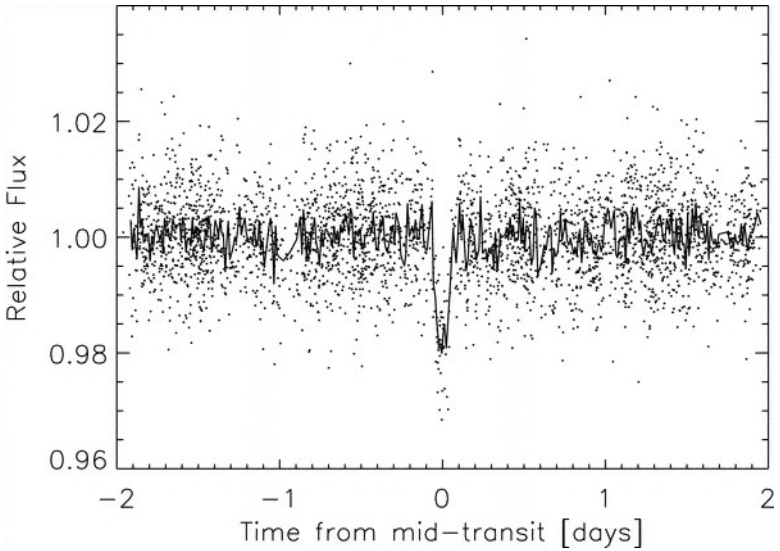


Planet Finding: Radial Velocity

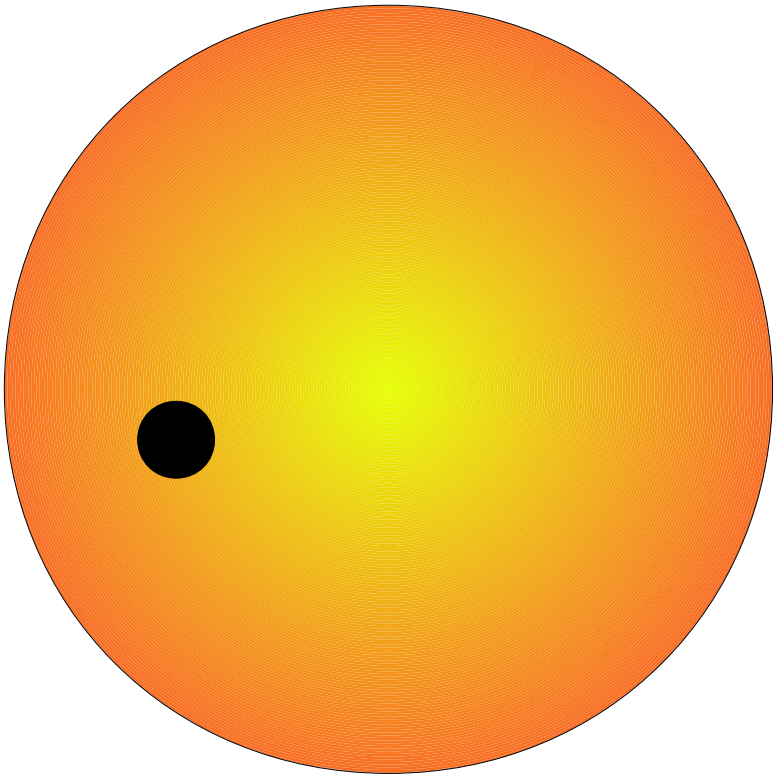


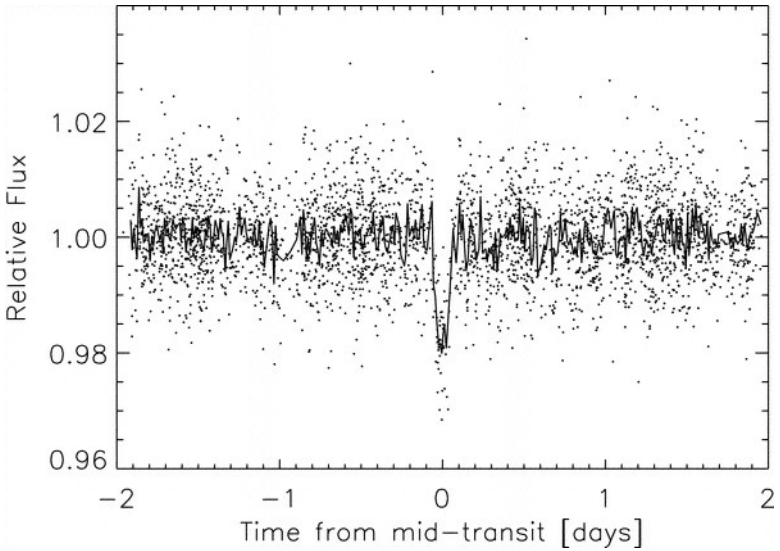
Planet Finding: Transits



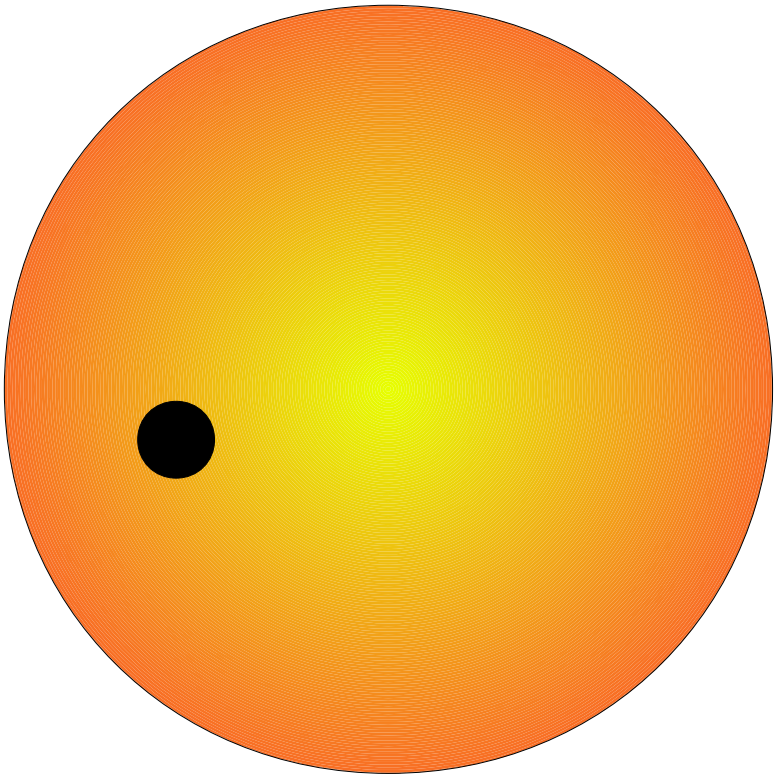


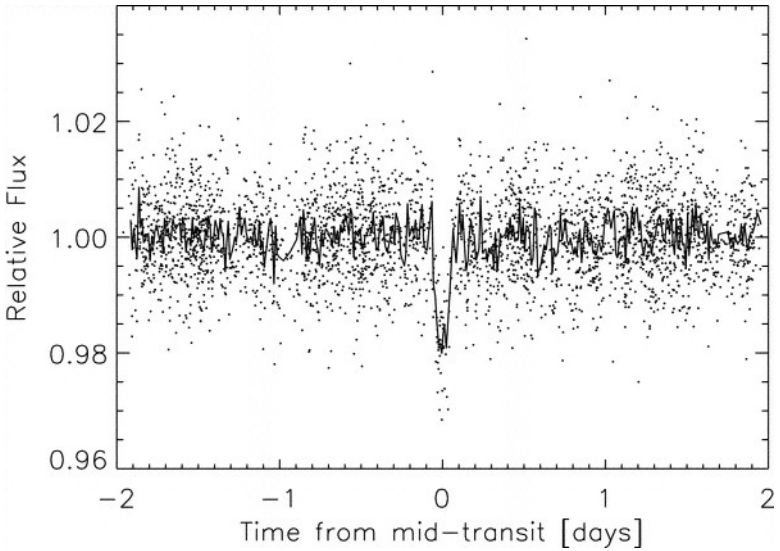
Planet Finding: Transits

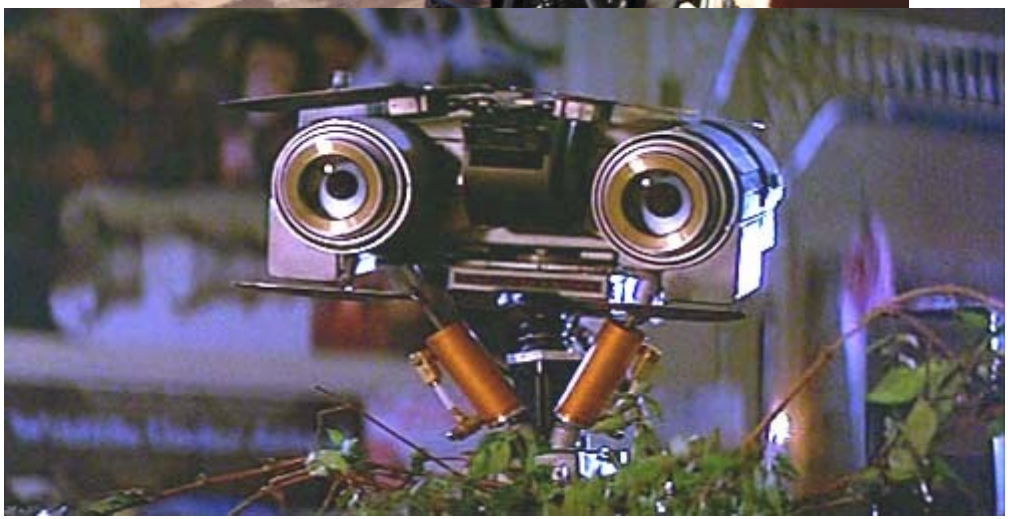




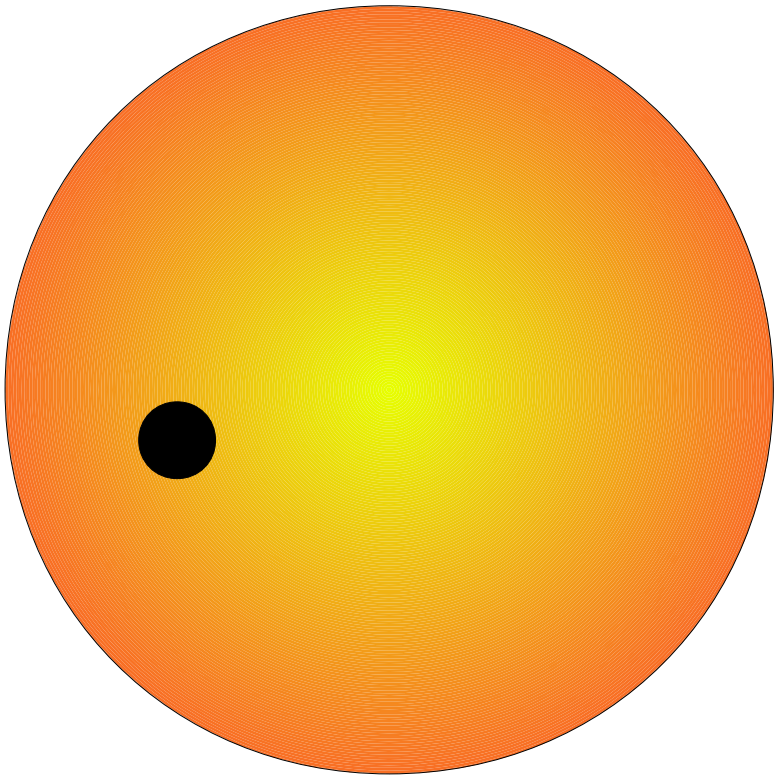
Planet Finding: Transits



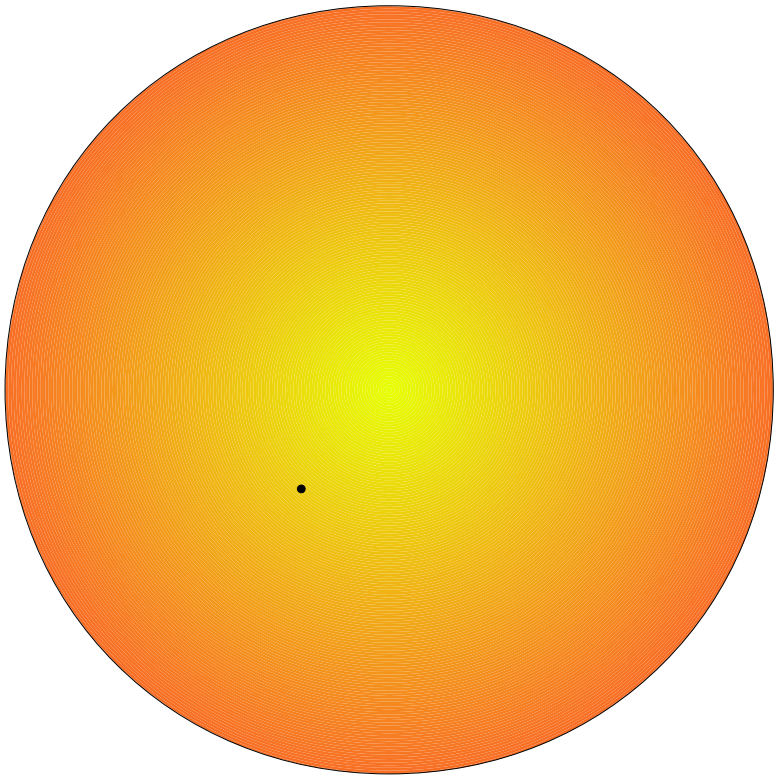




Planet Finding with Kepler



Jupiter: need 1 part per 1000.



Earth: need 1 part per 100,000.

Questions Addressed by Kepler

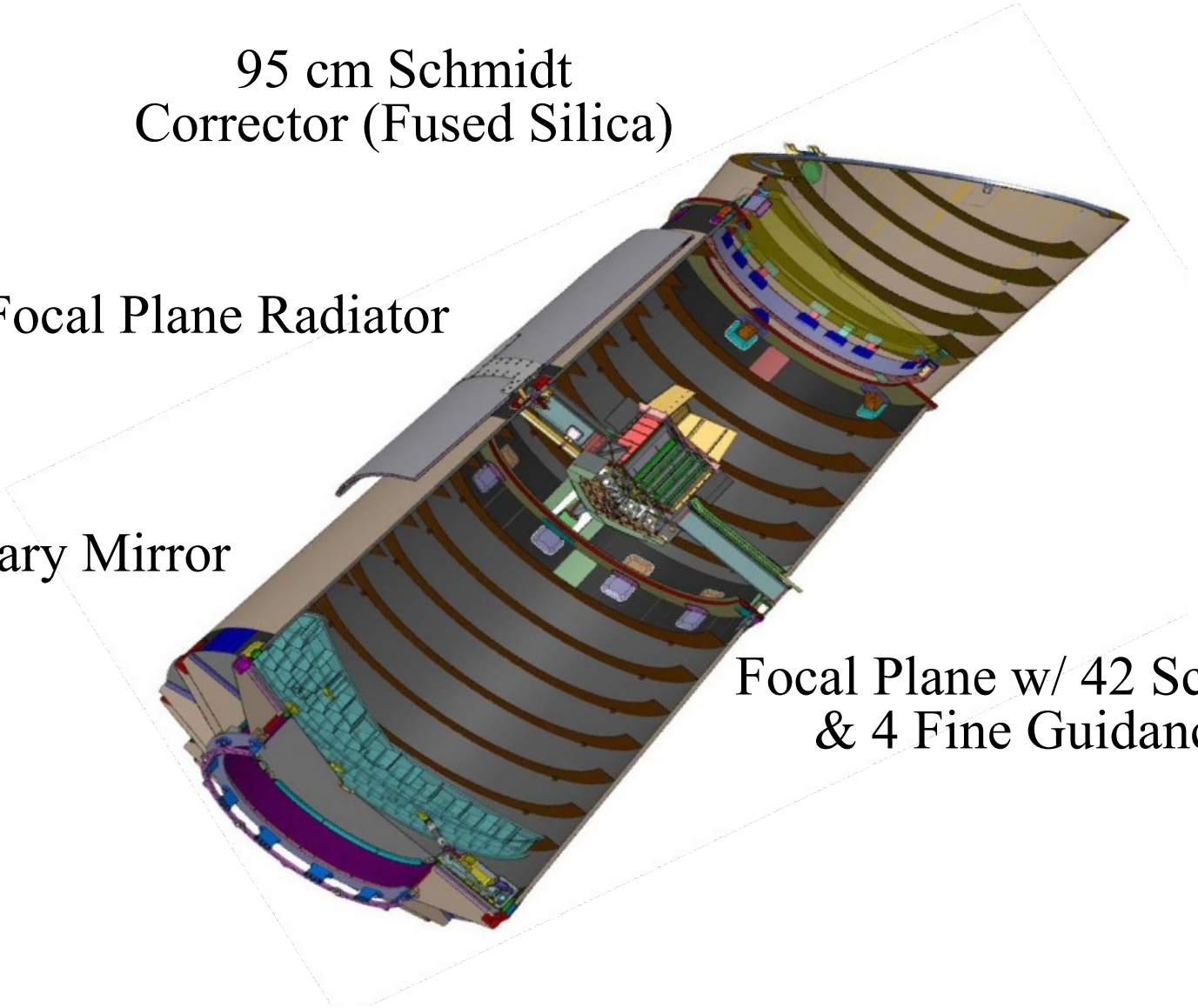
- What is the frequency of Earth-size planets in or near the Habitable Zone (HZ) of solar-like stars?
  - Are terrestrial planets common or rare?
- What are the distributions of planet sizes & semi-major axes?
- What are the frequency & orbital distributions of planets in multiple star systems?
- What are the distributions of semi-major axes, albedo, size, mass, and density of short-period giant planets?
- How are these properties associated with stellar characteristics?

Kepler Spacecraft

95 cm Schmidt
Corrector (Fused Silica)

Focal Plane Radiator

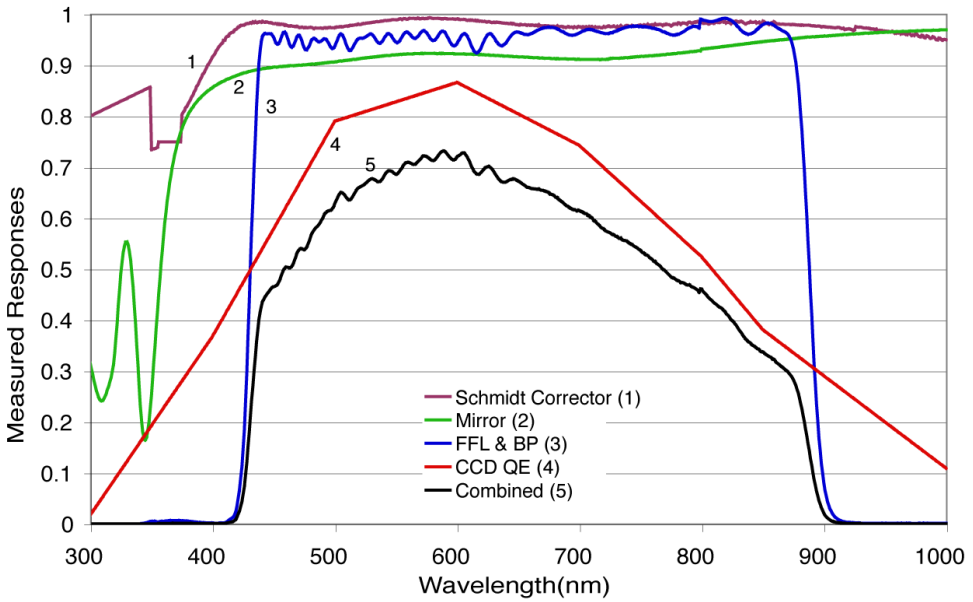
1.4m Primary Mirror



Focal Plane w/ 42 Science CCD's
& 4 Fine Guidance Sensors

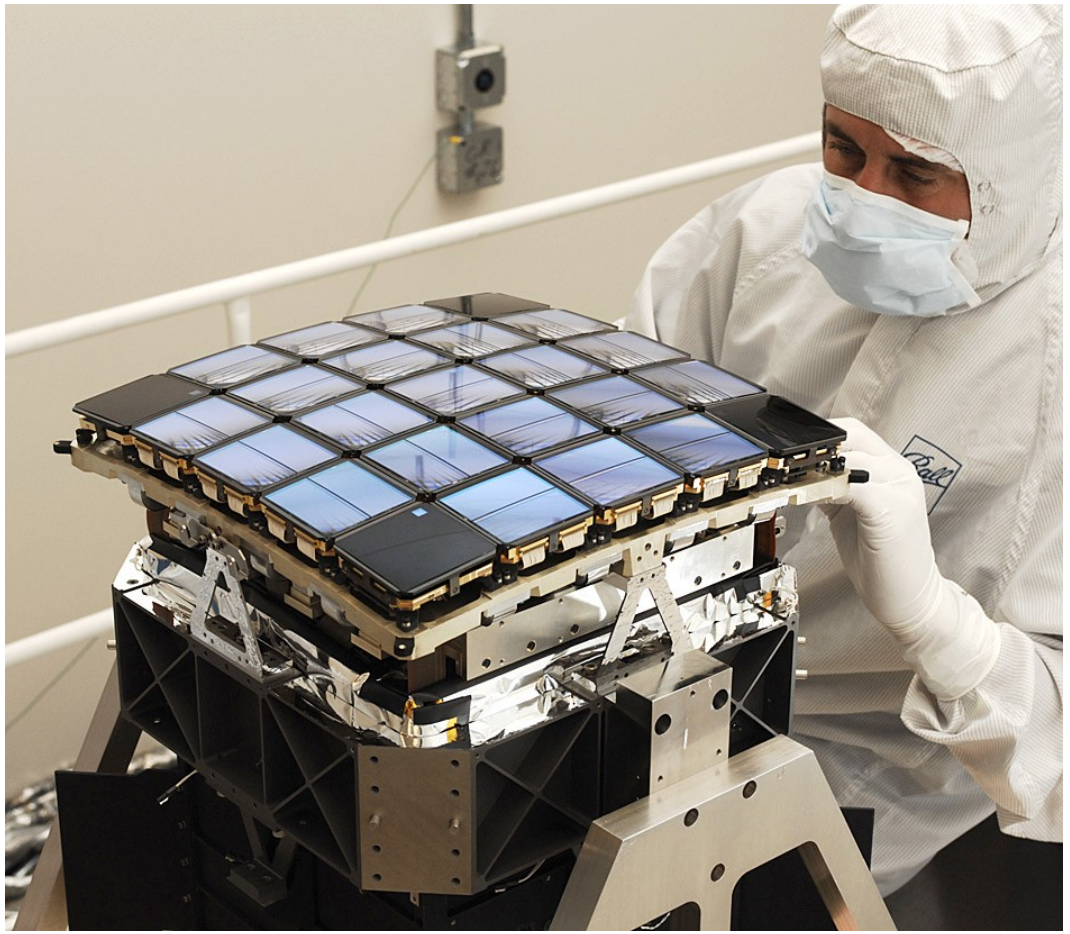
Kepler Instrument Design

Overall spectral throughput.



Kepler primary mirror

Kepler Photometer

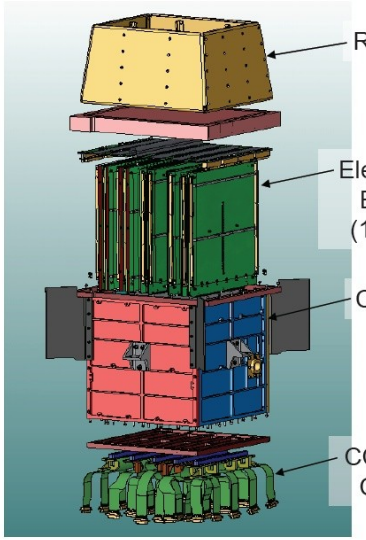


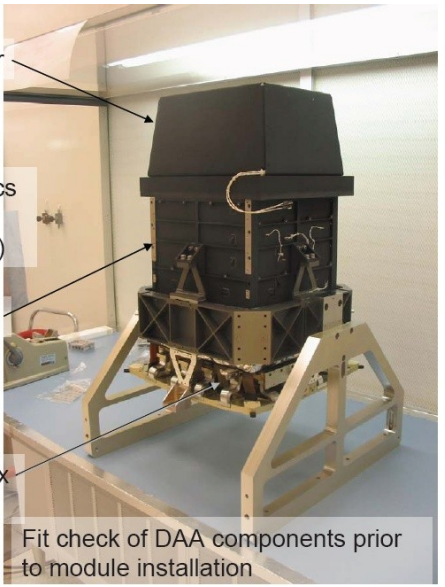
42 CCD chips, 95 million pixels

Continuously monitor
~150,000 target stars

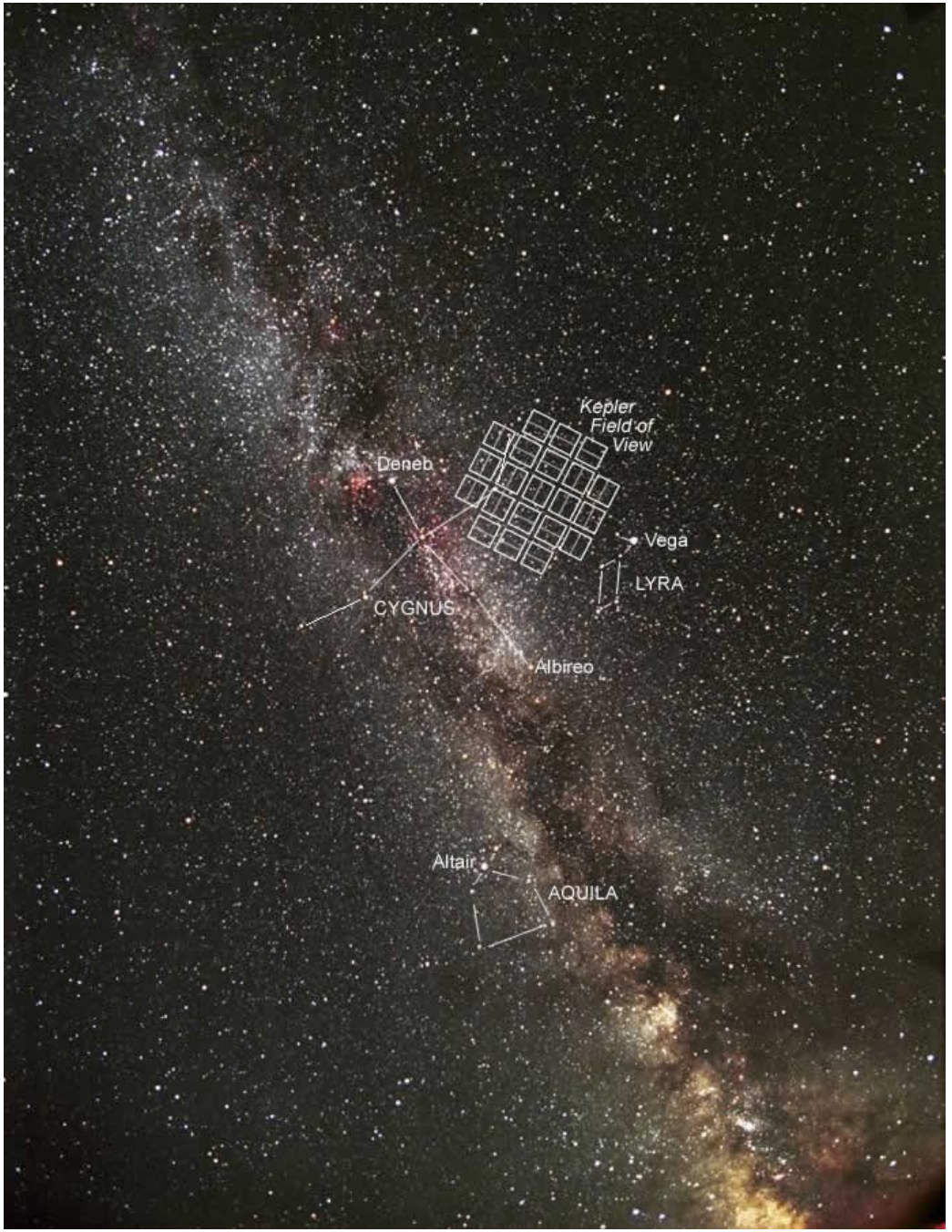
Images are de-focused

Only target pixels are
sent back to Earth



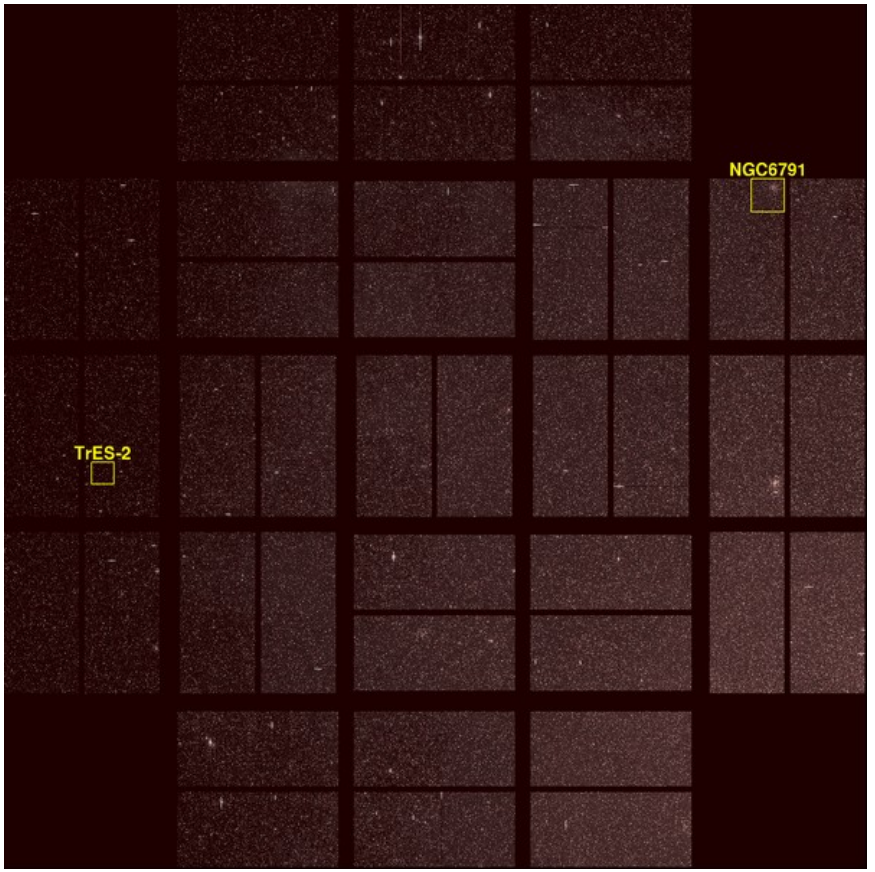

Fit check of DAA components prior to module installation

Kepler Field of View

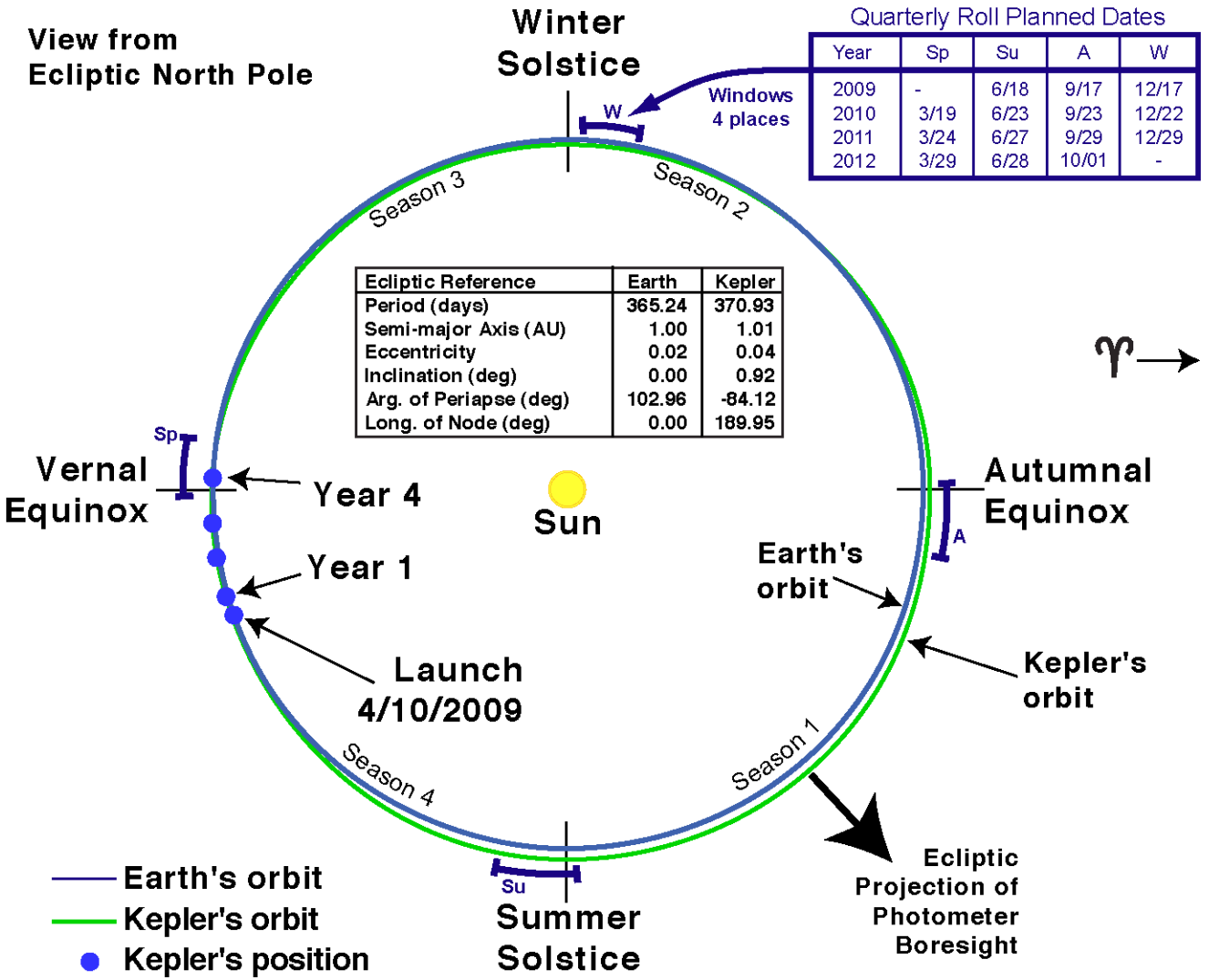


~100 square degrees

First light image



Kepler Orbit



Ground-based Program

Keck 10m

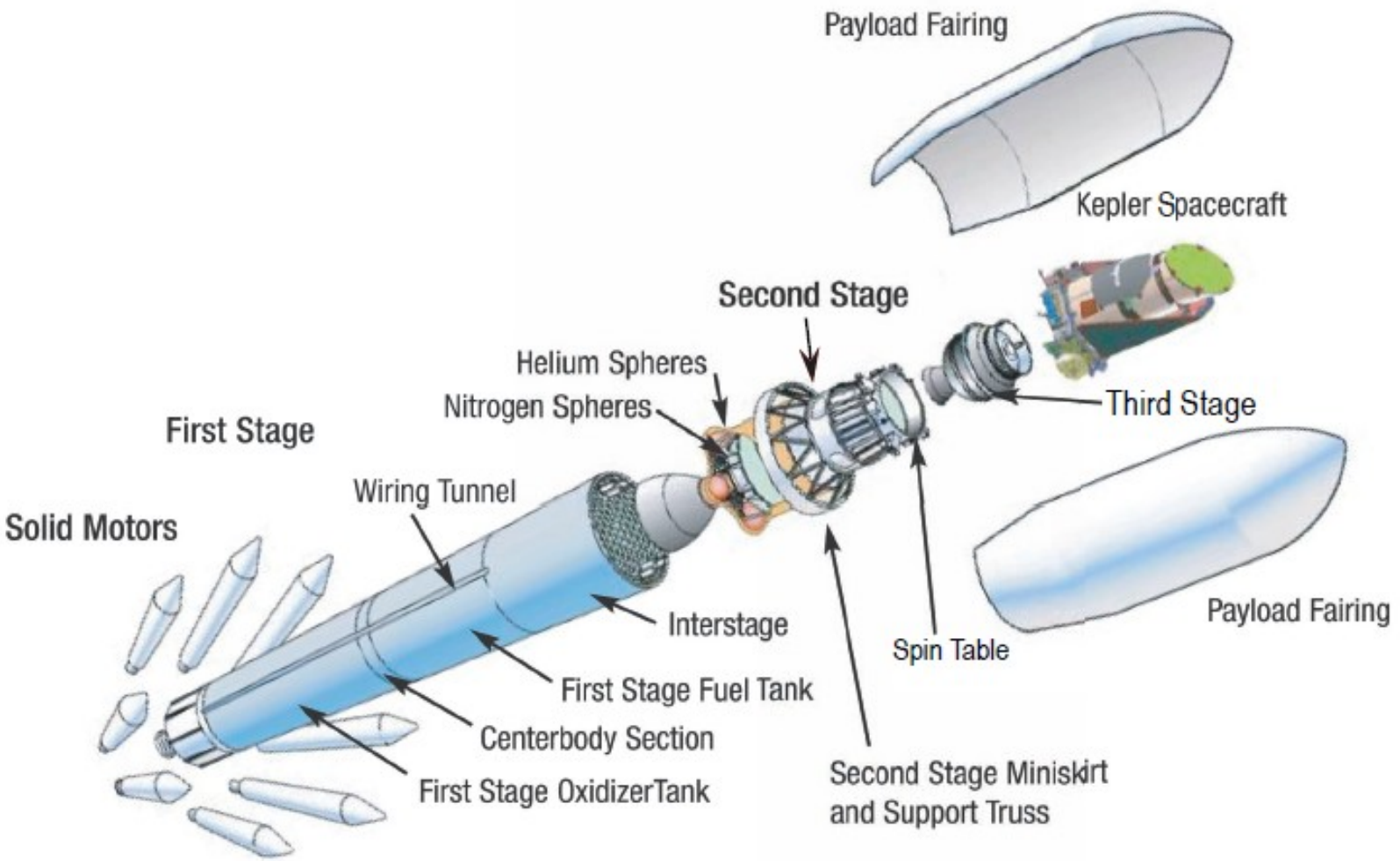
HET 9m

MMT 6.5m

- Kepler input catalog
  - Stellar classification for target selection
- Low resolution spectroscopy
  - Used to remove some false positive systems
- High spacial resolution imaging
  - Adaptive optics and speckle interferometry
  - Used to remove confusion due to crowding
- High resolution spectroscopy
  - Used to measure the masses of detected planets
  - Used to confirm lack of detectable signal for small planets
- Cannot confirm planet nature with transits alone!

Many additional telescopes are used in ground-based program.

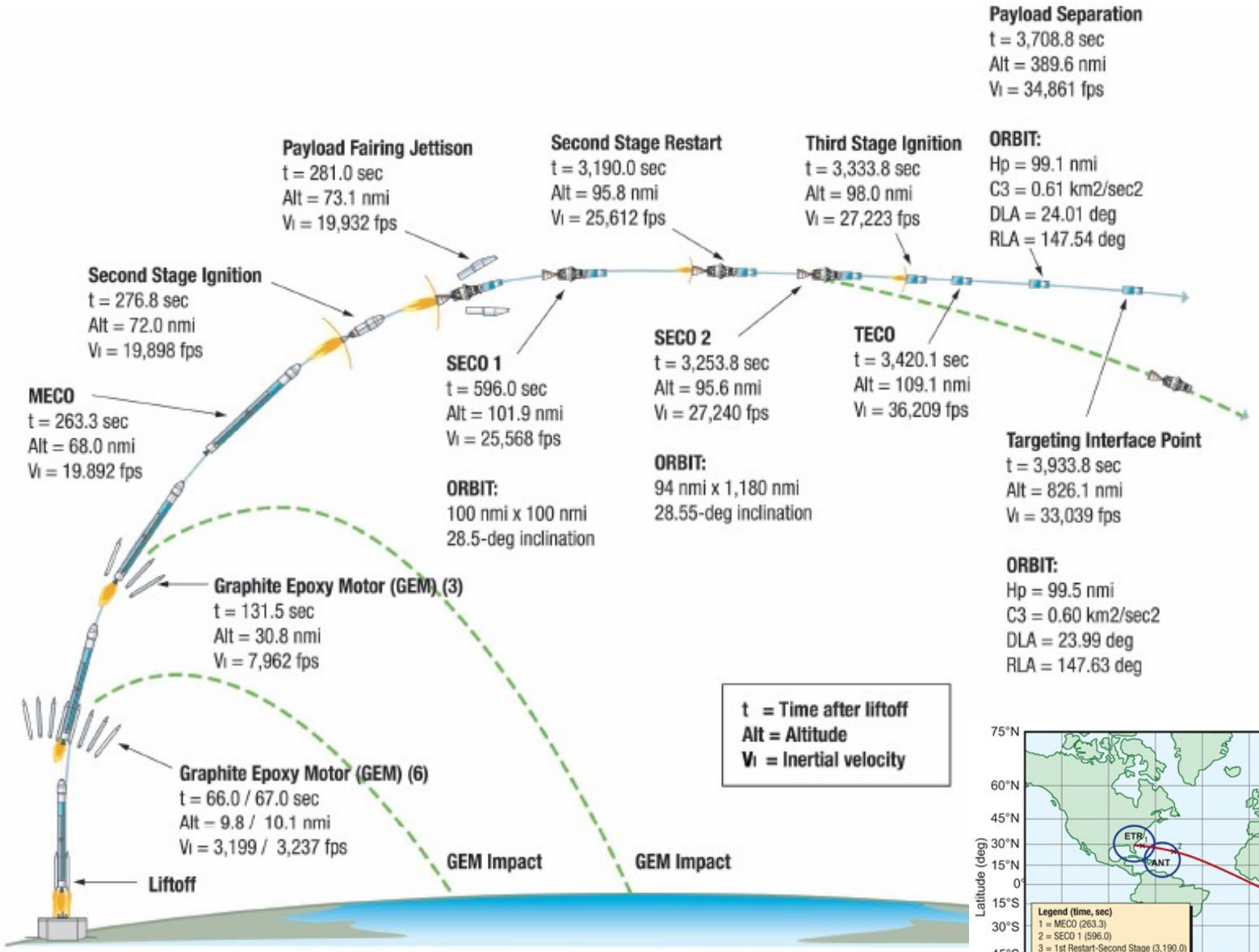
Kepler Launch Vehicle



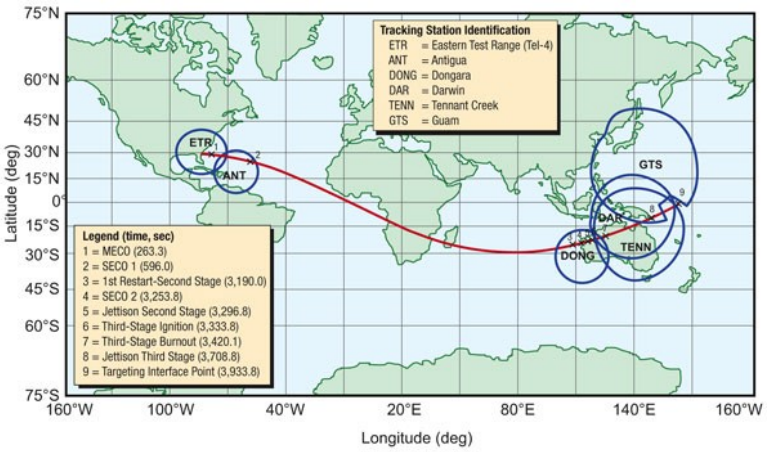
Delta Launch Vehicle with Kepler Spacecraft

Before and During

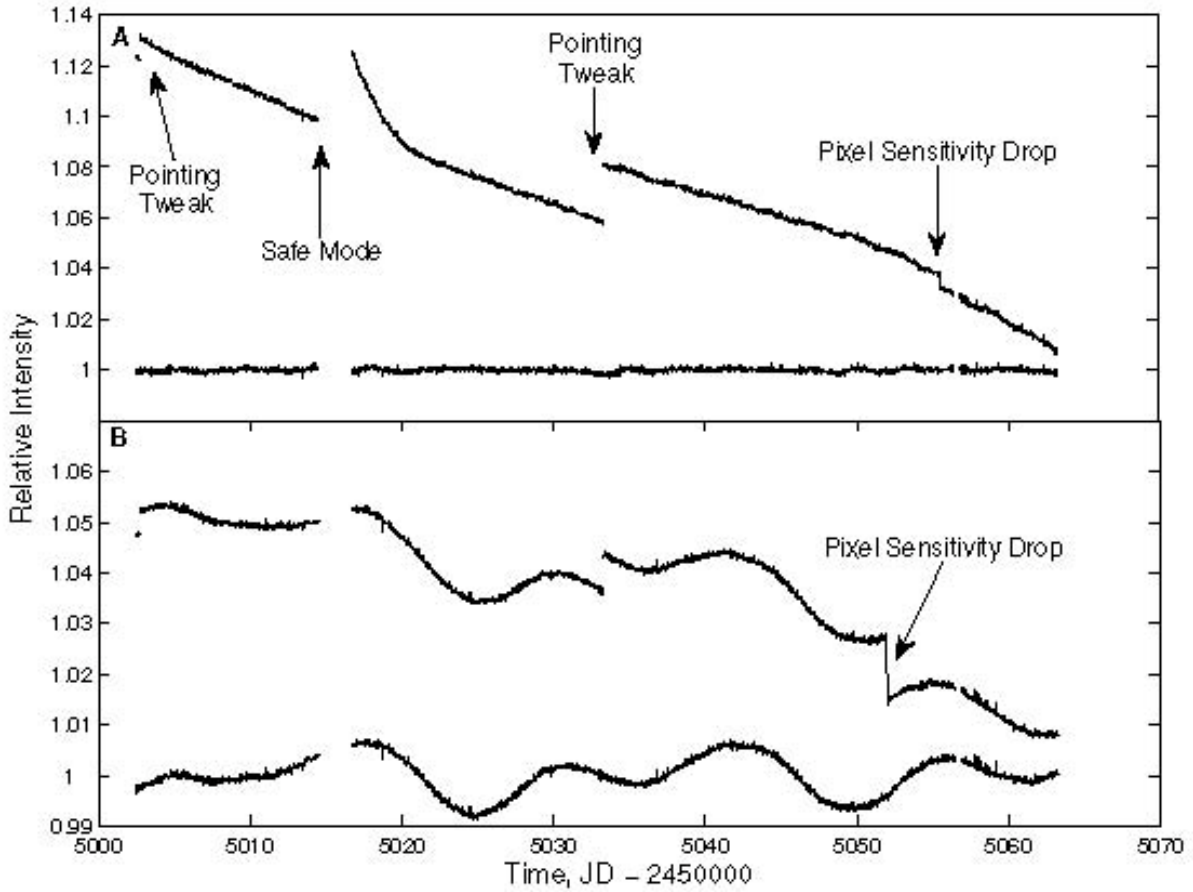
Launch Sequence



Kepler Launch Profile



Time Series Data

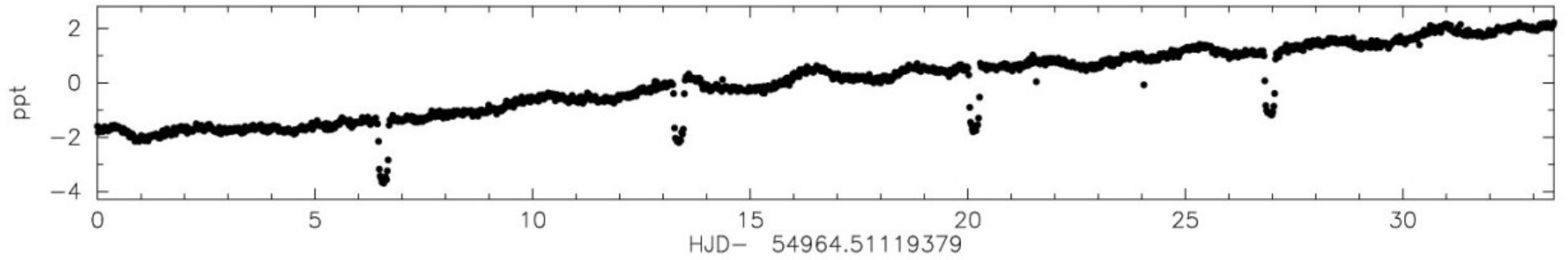


Before correction

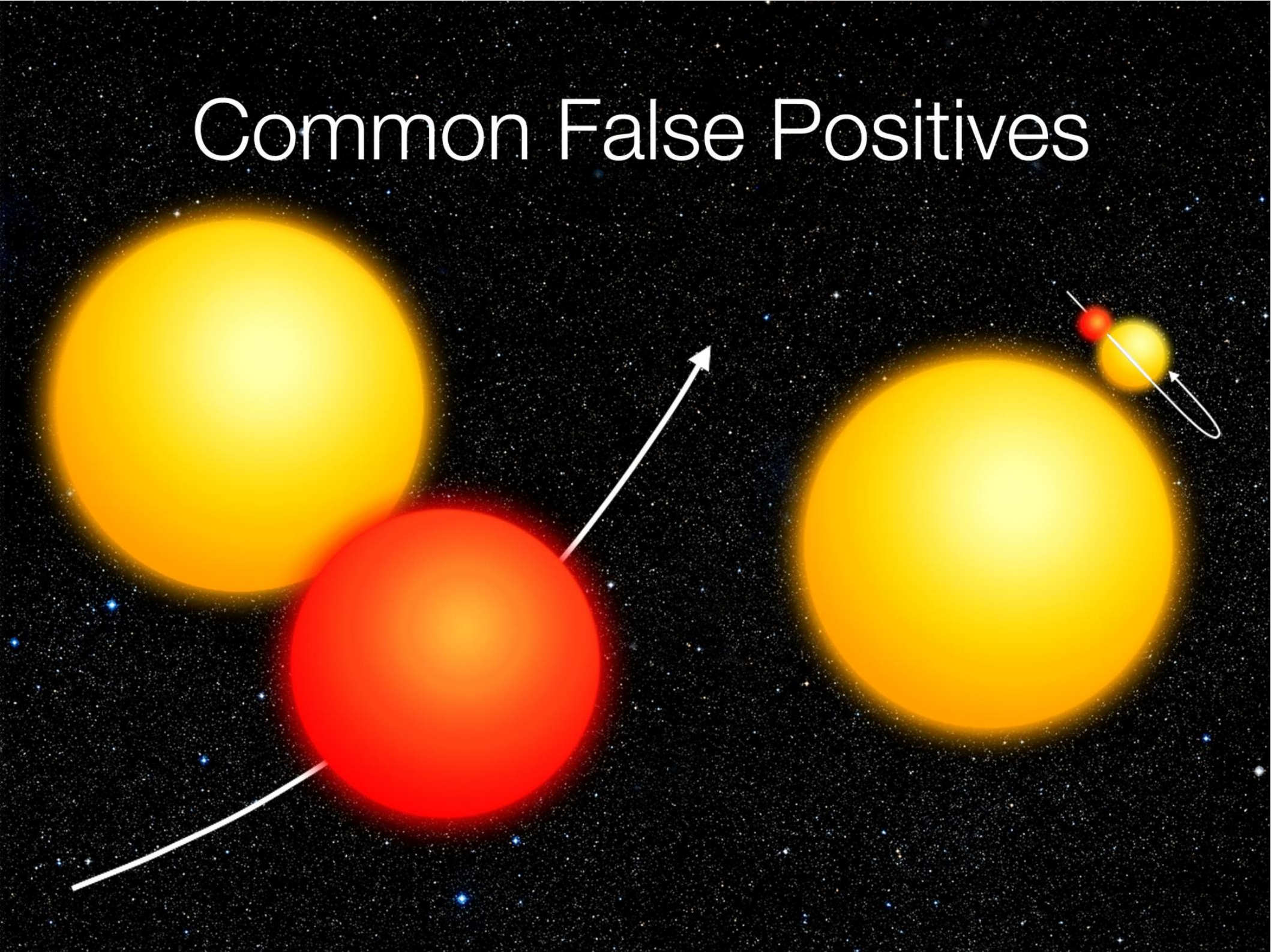
After correction

Before correction

After correction



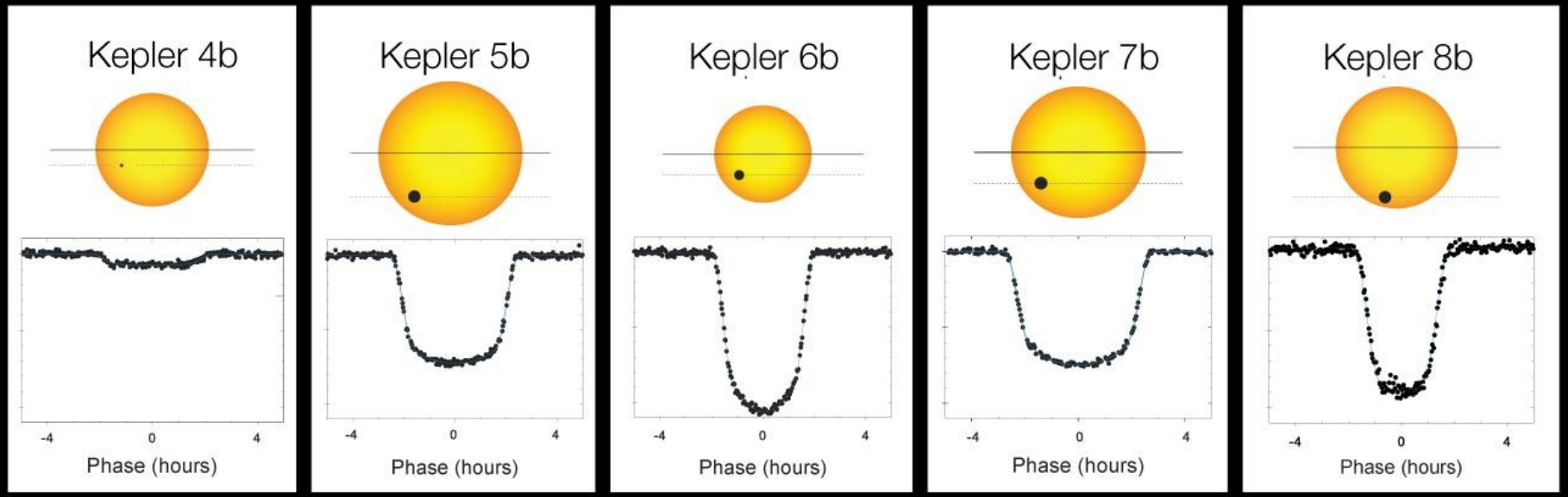
Common False Positives



Many are Candidates, Few are Planets

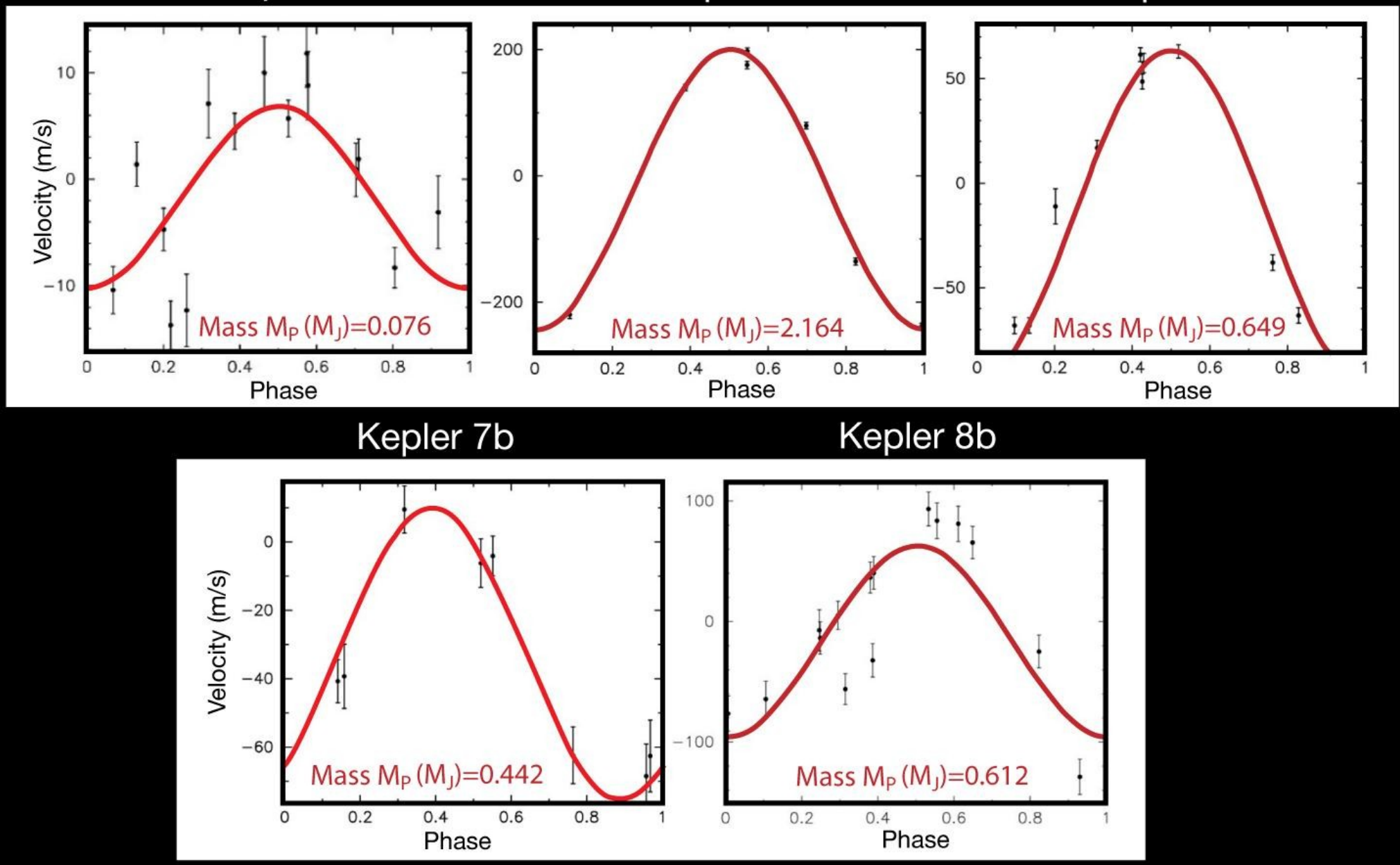
- SNR > 7 to rule out statistical fluctuations
- Three or more transits to confirm periodic signal
- Light curve depth, shape, and duration
- Image subtraction to identify signals from background stars
- Movement of stellar centroid to remove high-mass companions
- Radial velocity
  - Medium precision to rule out stellar companions
  - High precision to measure mass and confirm discoveries
  - Rossiter-McLaughlin effect also to confirm planets
- High spatial resolution to identify extremely close background stars

Transit Light Curves

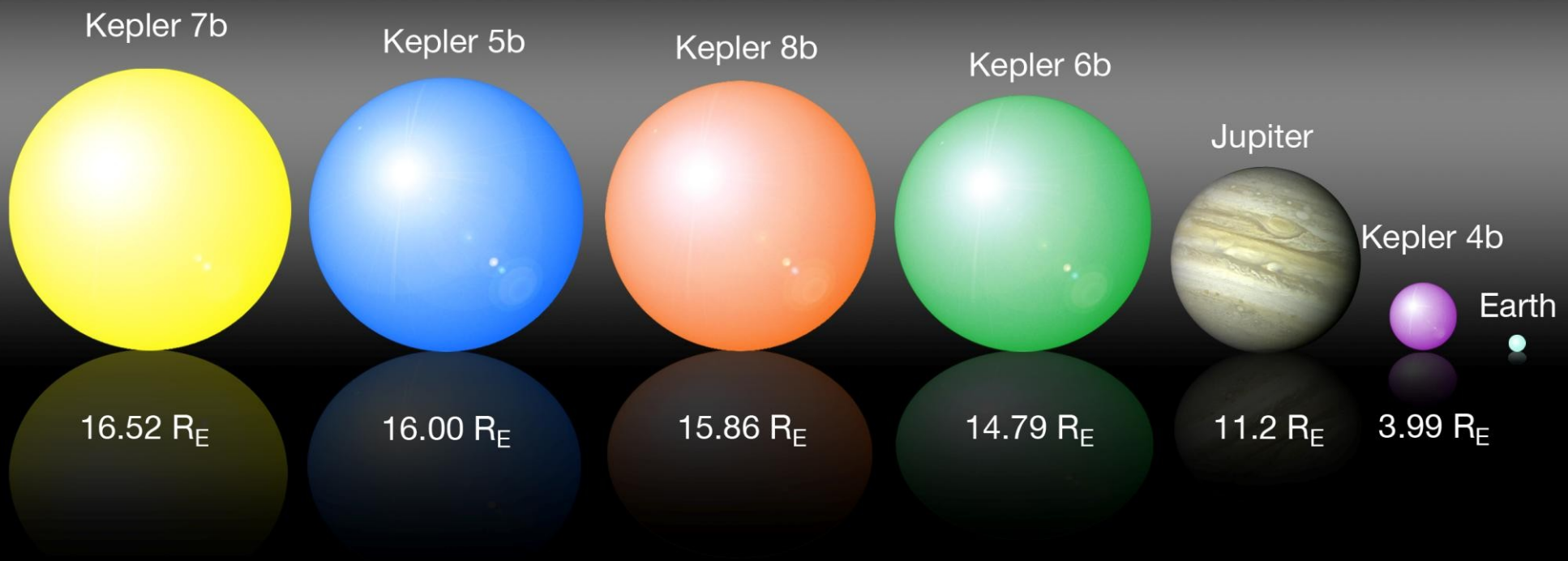


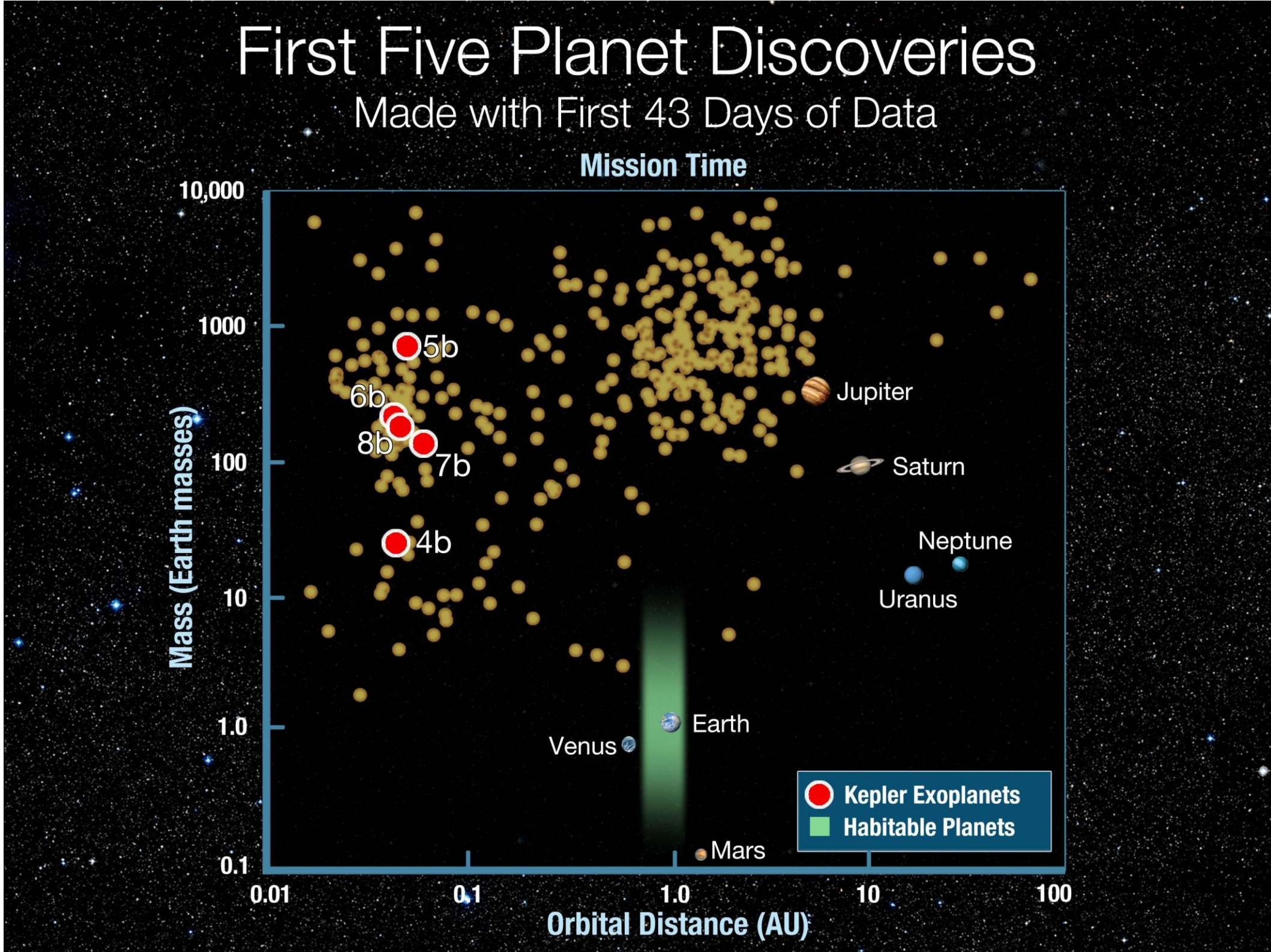
	Kepler 4b	Kepler 5b	Kepler 6b	Kepler 7b	Kepler 8b
Orbital Period (days)	*3.2 days*	*3.5 days*	*3.2 days*	*4.9 days*	*3.5 days*
Size (R_E)	*4.31*	*18.8*	*15.0*	*16.9*	*18.3*

Radial Velocity of Host Stars



Planet Size


Kepler 7b
Kepler 5b
Kepler 8b
Kepler 6b
Jupiter
Kepler 4b
Earth
16.52 R_E
16.00 R_E
15.86 R_E
14.79 R_E
11.2 R_E
3.99 R_E

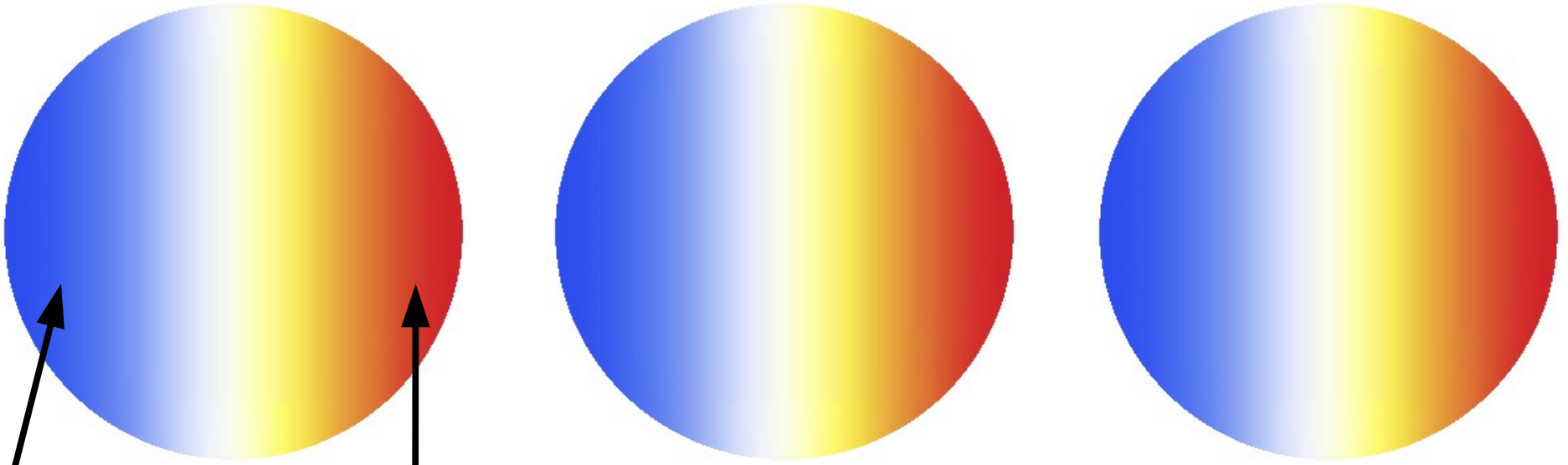

First Five Planet Discoveries
Made with First 43 Days of Data
Mission Time
10,000
1000
100
10
1.0
0.1
Mass (Earth masses)
5b
6b
8b
7b
4b
Jupiter
Saturn
Neptune
Uranus
Earth
Venus
Mars
Kepler Exoplanets
Habitable Planets
0.01
0.1
1.0
10
100
Orbital Distance (AU)

Additional Science

- Planet formation, evolution, and dynamics
- Planet properties
- Stellar astrophysics, pulsation, and evolution
- Bug collecting

Planet Formation and Dynamics

The Rossiter-McLaughlin effect for rotating stars

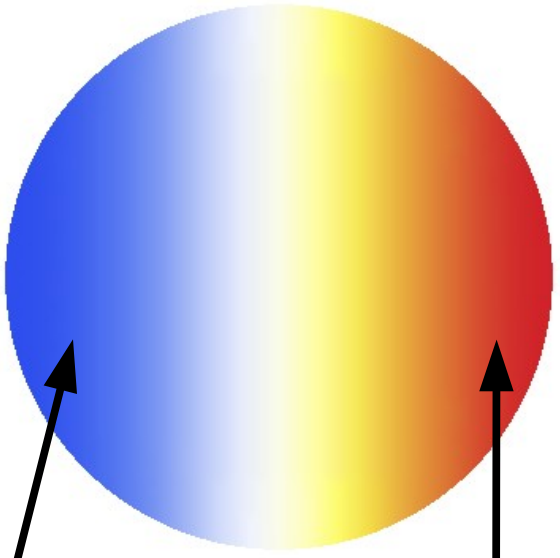


Approaching side
is blueshifted

Receding side
is redshifted

Planet Formation and Dynamics

The Rossiter-McLaughlin effect for rotating stars



Approaching side
is blueshifted

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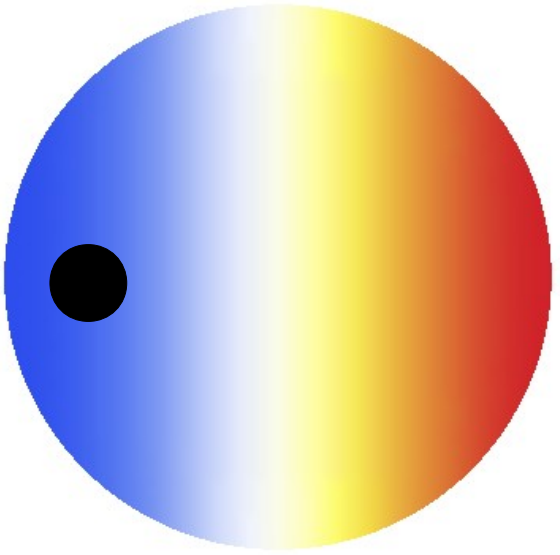
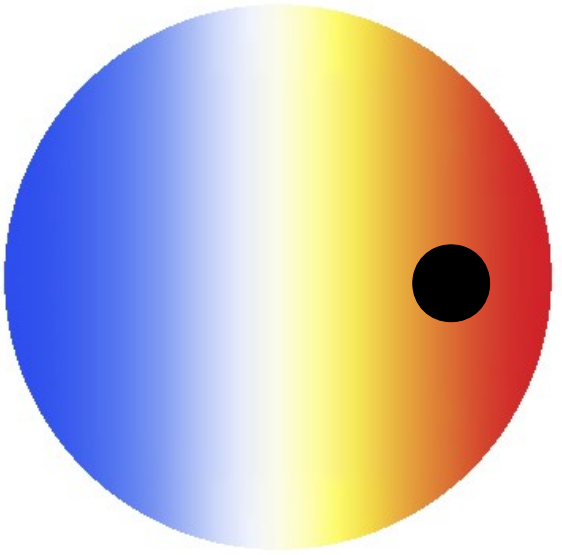


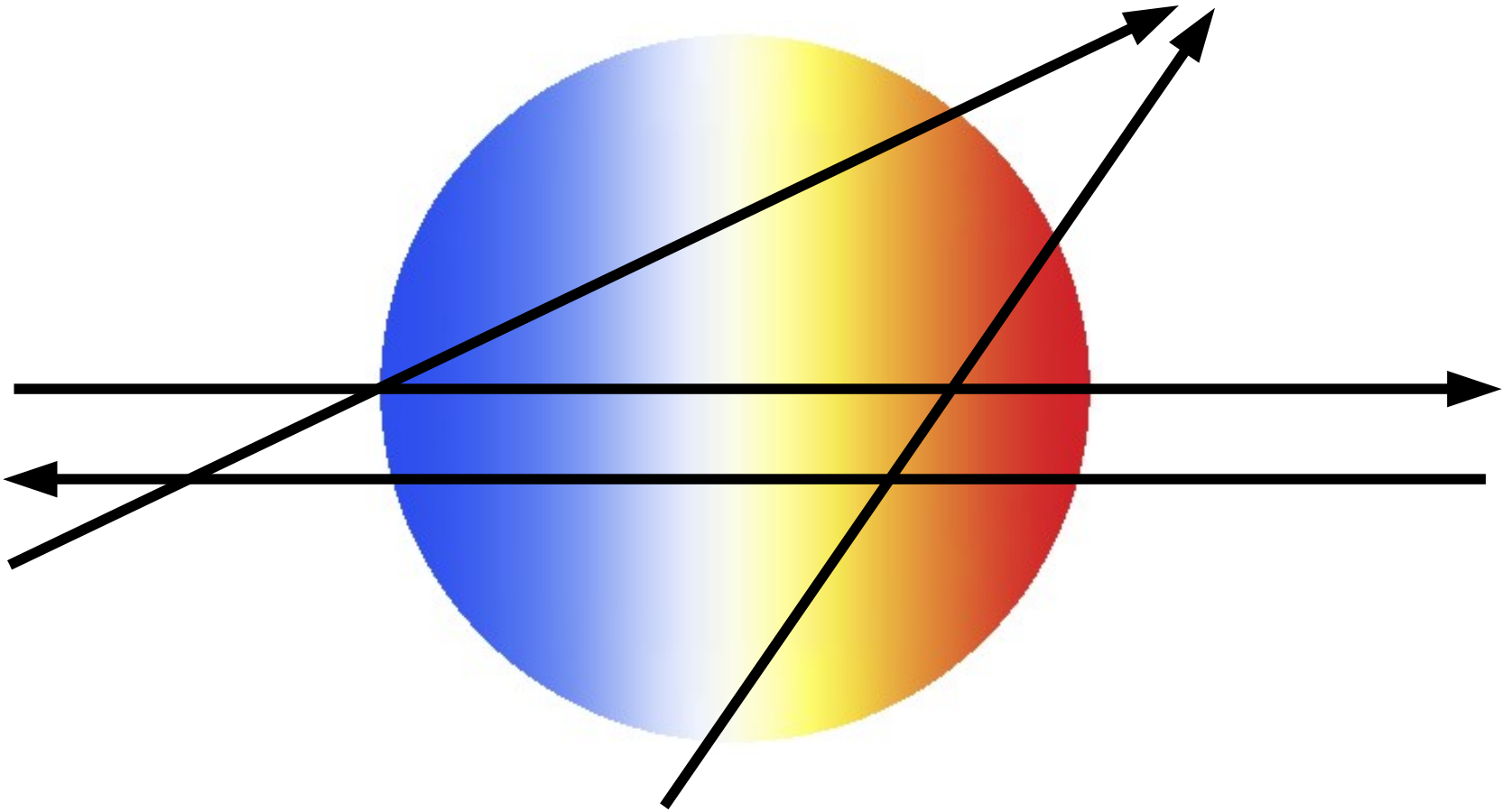
A planet on this side
causes an apparent
redshift.



A planet on this side
causes an apparent
blueshift.

Planet Formation and Dynamics

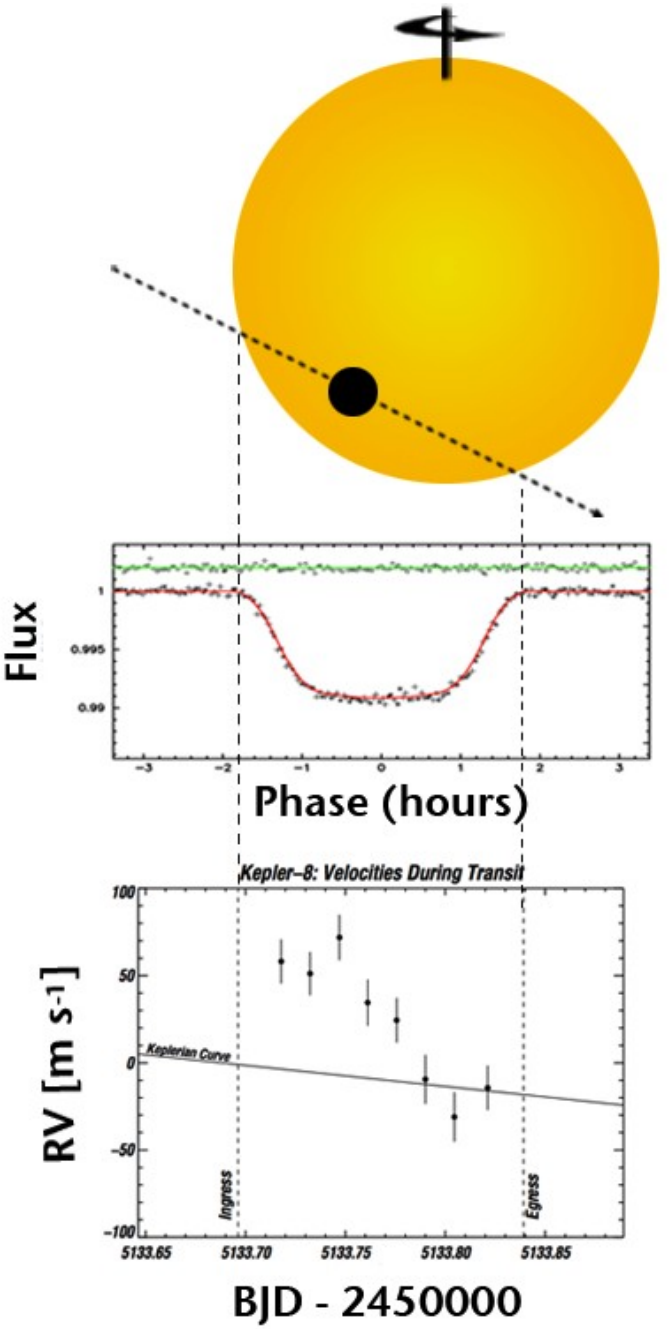
The Rossiter-McLaughlin effect for rotating stars



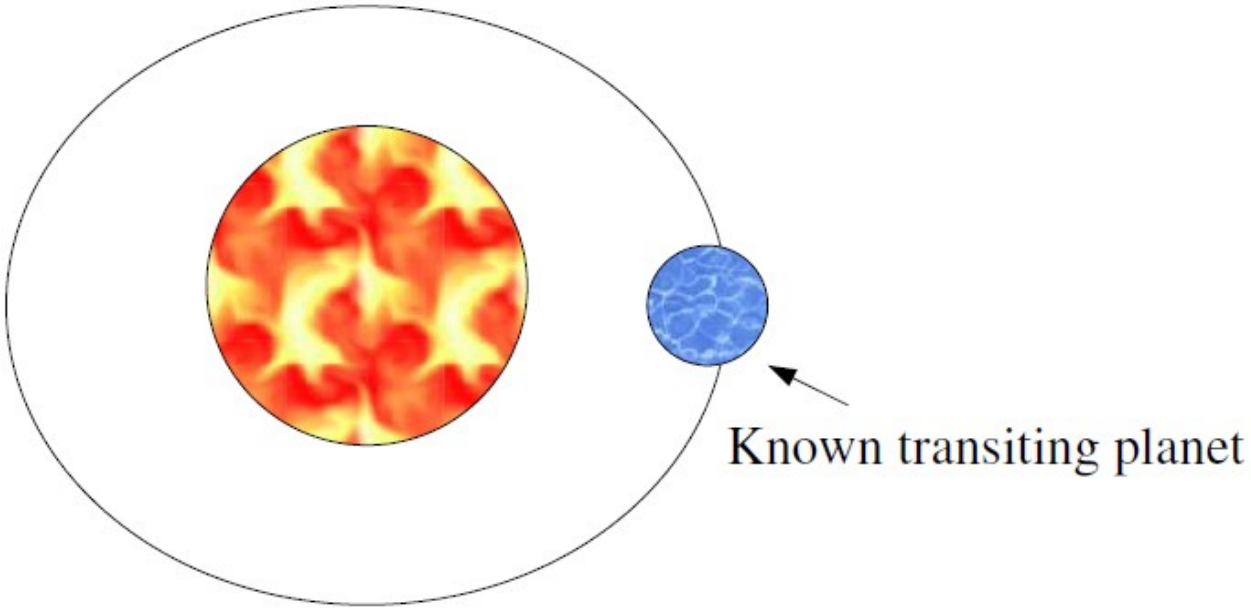
Transits along different trajectories give different signatures.

Planet Formation and Dynamics

- Rossiter-McLaughlin effect measured on Kepler-8
- These measurements were used to confirm the planetary nature of the companion
- This system has a prograde orbit
- Note: the tip of the star towards the observer can be measured with asteroseismological analysis

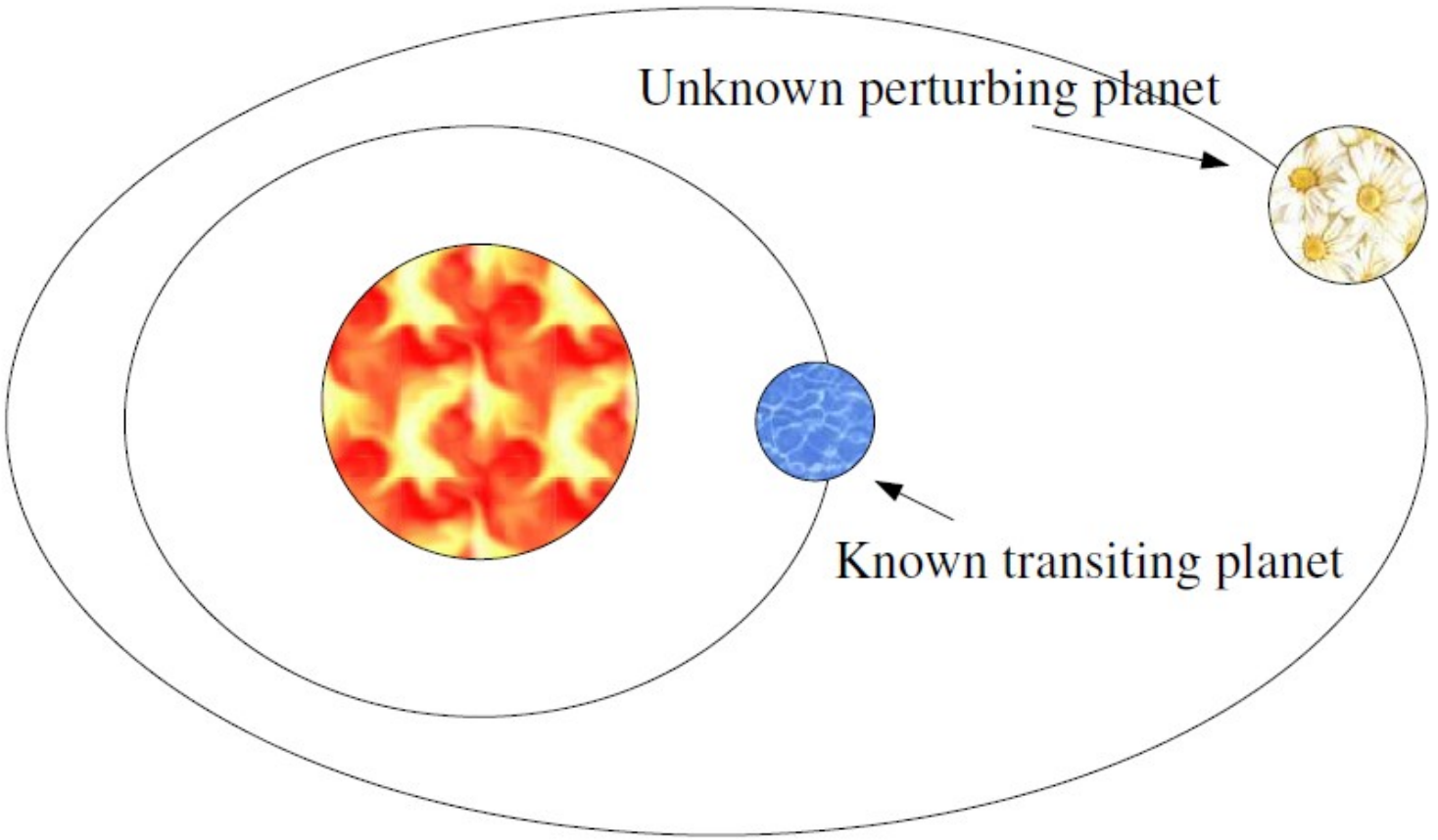


Planet Formation and Dynamics



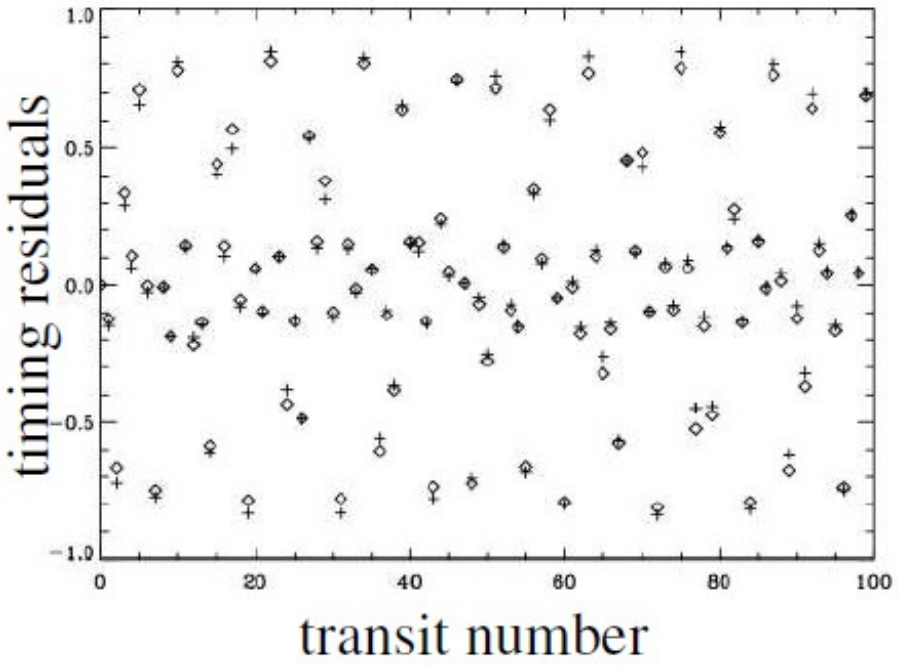
Transit times are equally spaced.

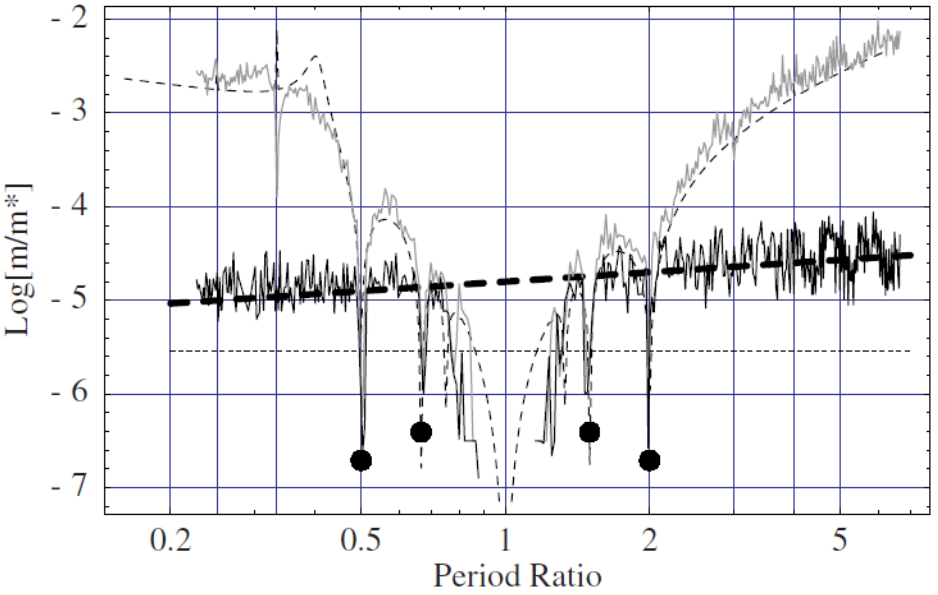
Planet Formation and Dynamics



Transit times are <u>NOT</u> equally spaced.

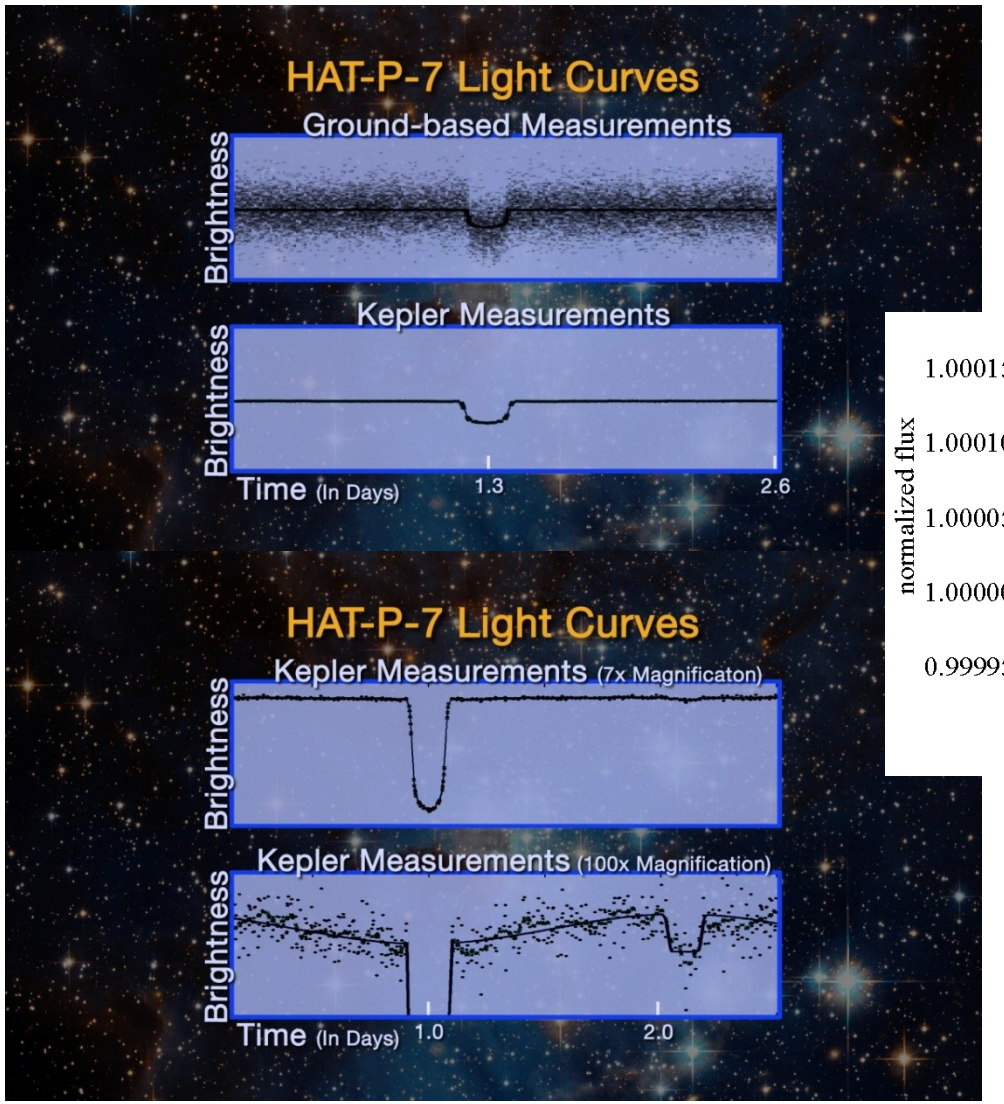
Planet Formation and Dynamics



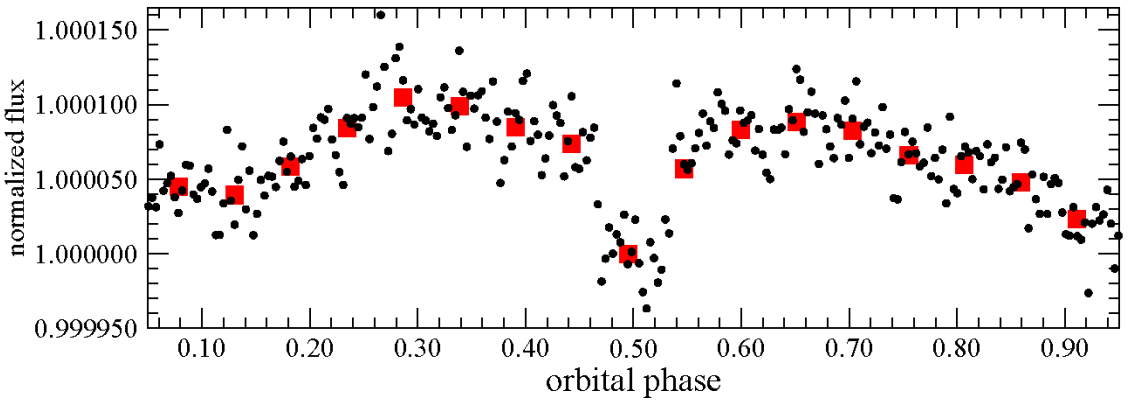


Transit timing variations (TTV) can be used to find additional planets, constrain planet formation models, and give complementary estimates of important system parameters (e.g. stellar mass).

Planet – Star Interaction

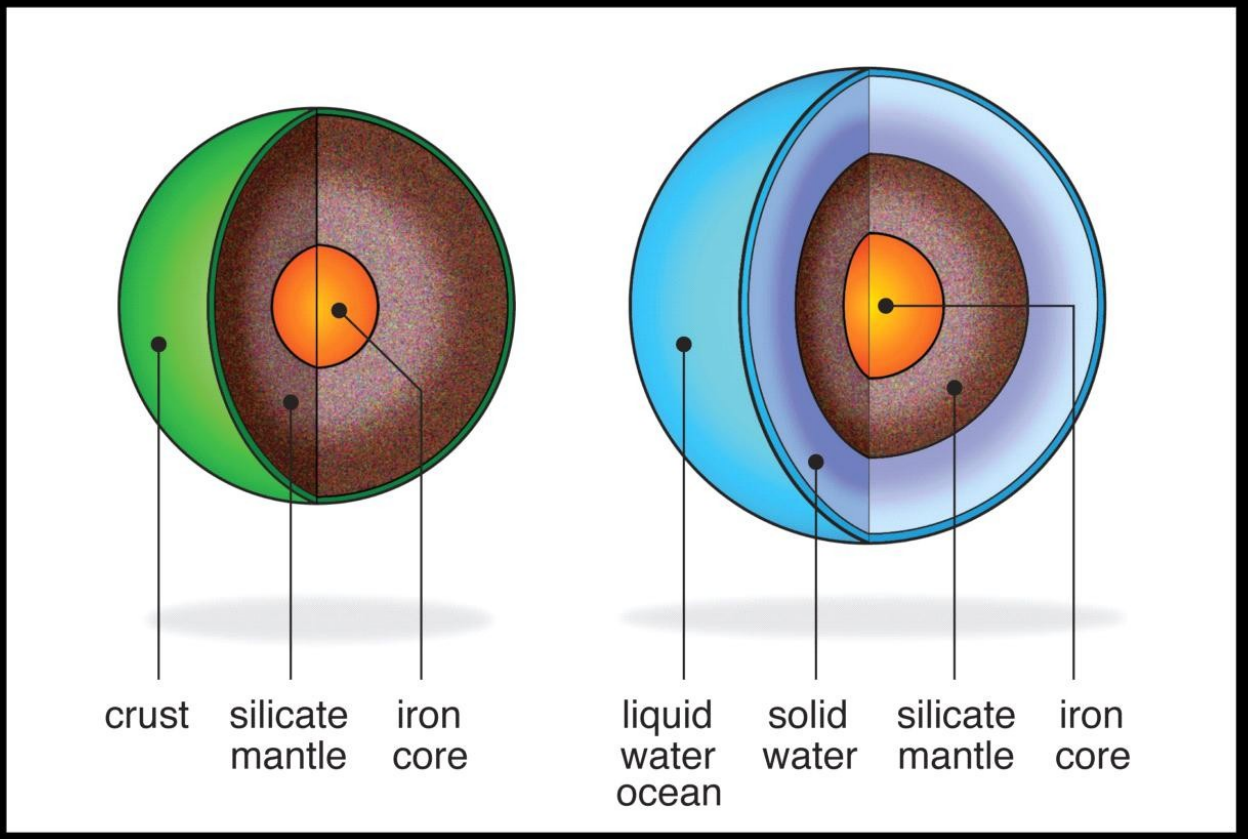


Detection of ellipsoidal variations in HAT-P-7.

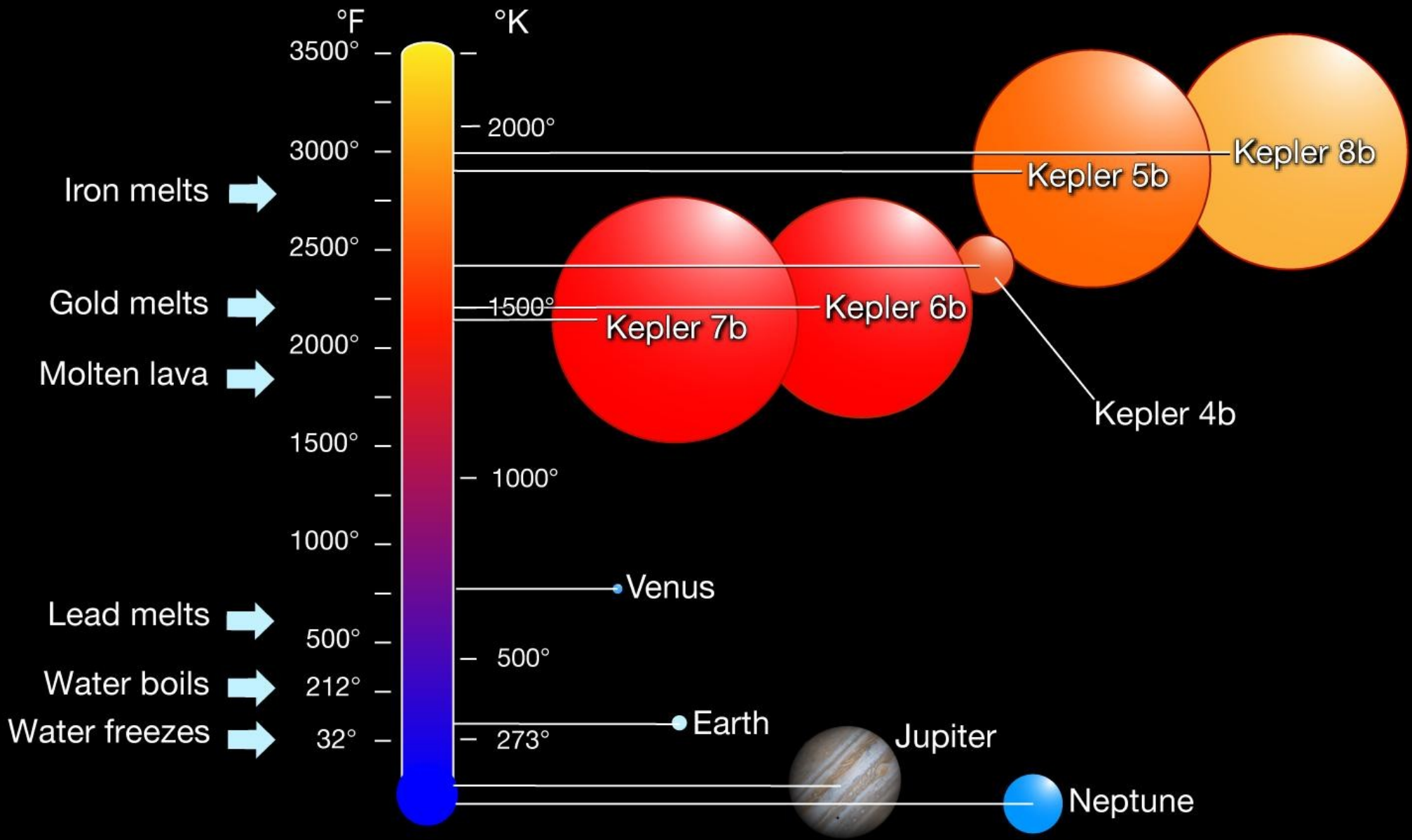


Planetary Properties

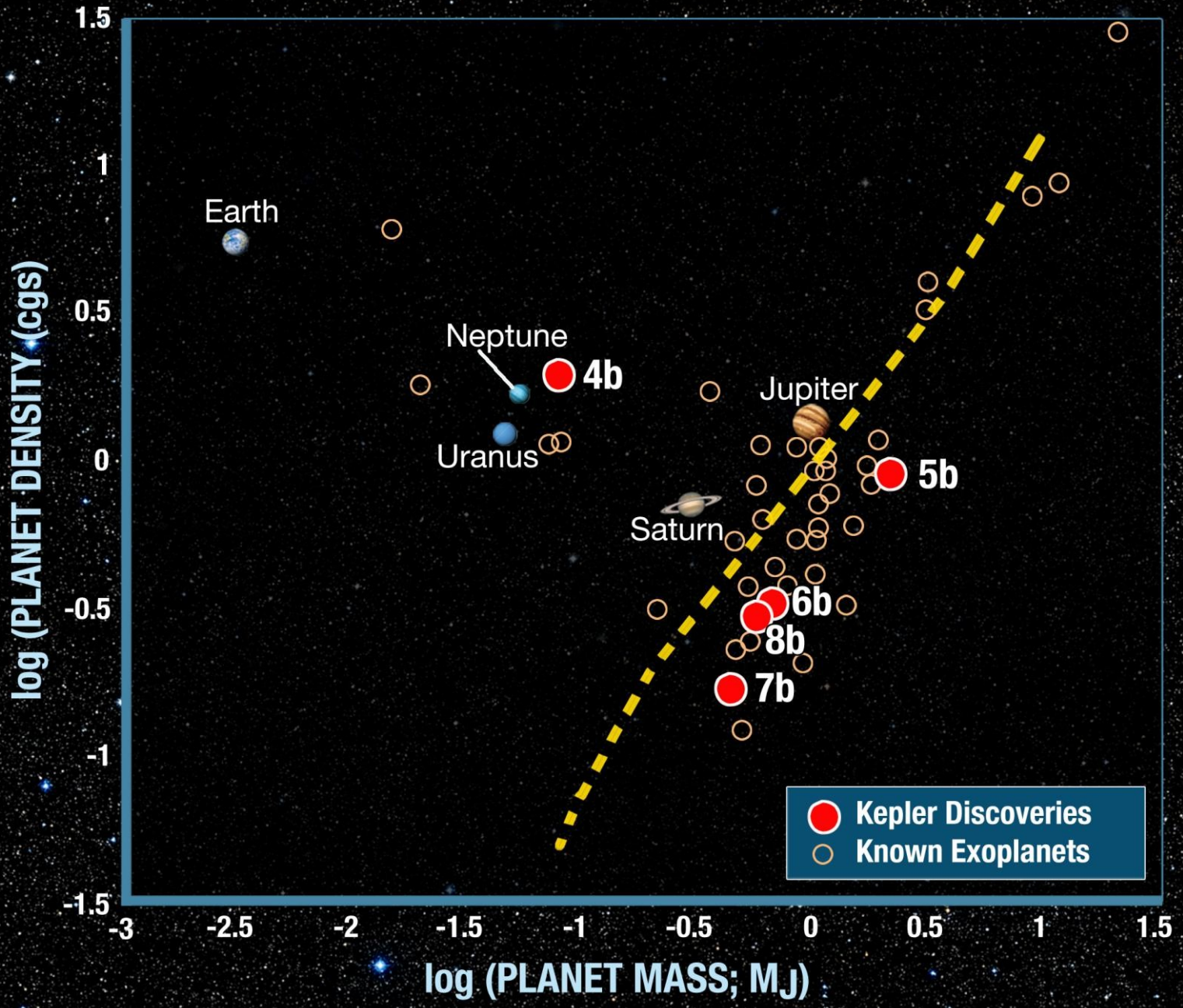
Super-Earths



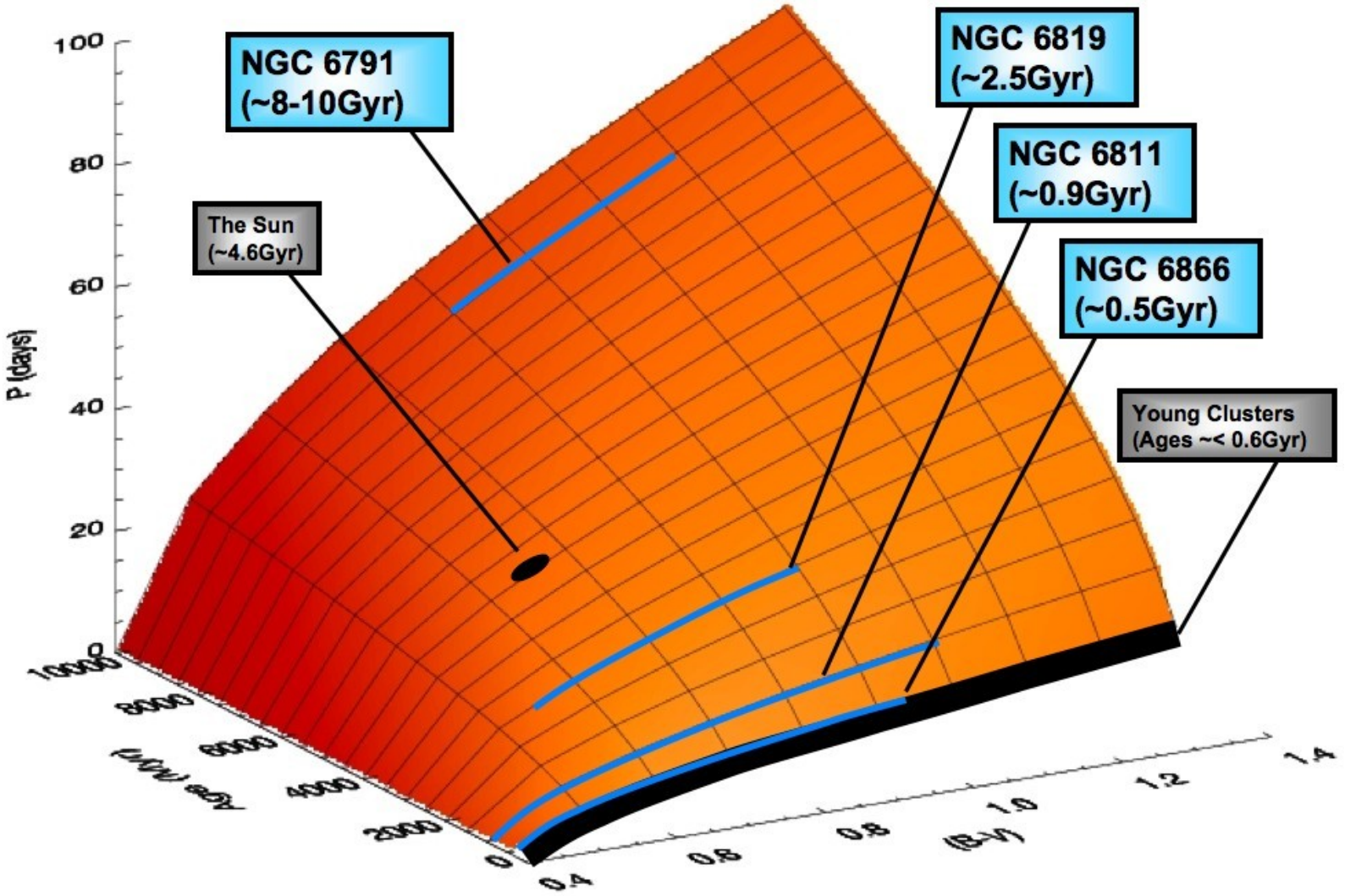
Planet Temperature & Size



Variation of Planet Density with Mass

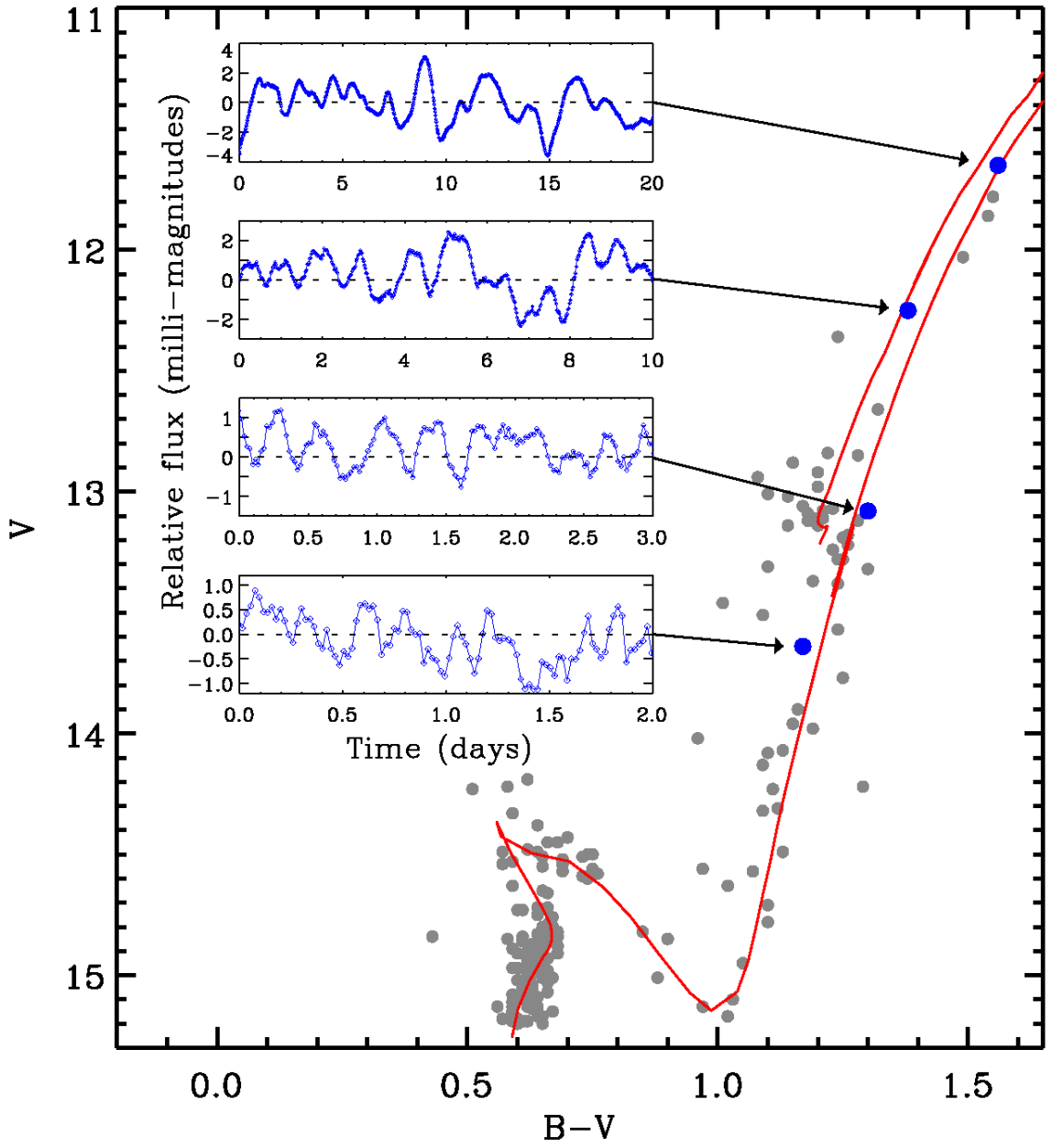


Stellar Evolution with Kepler



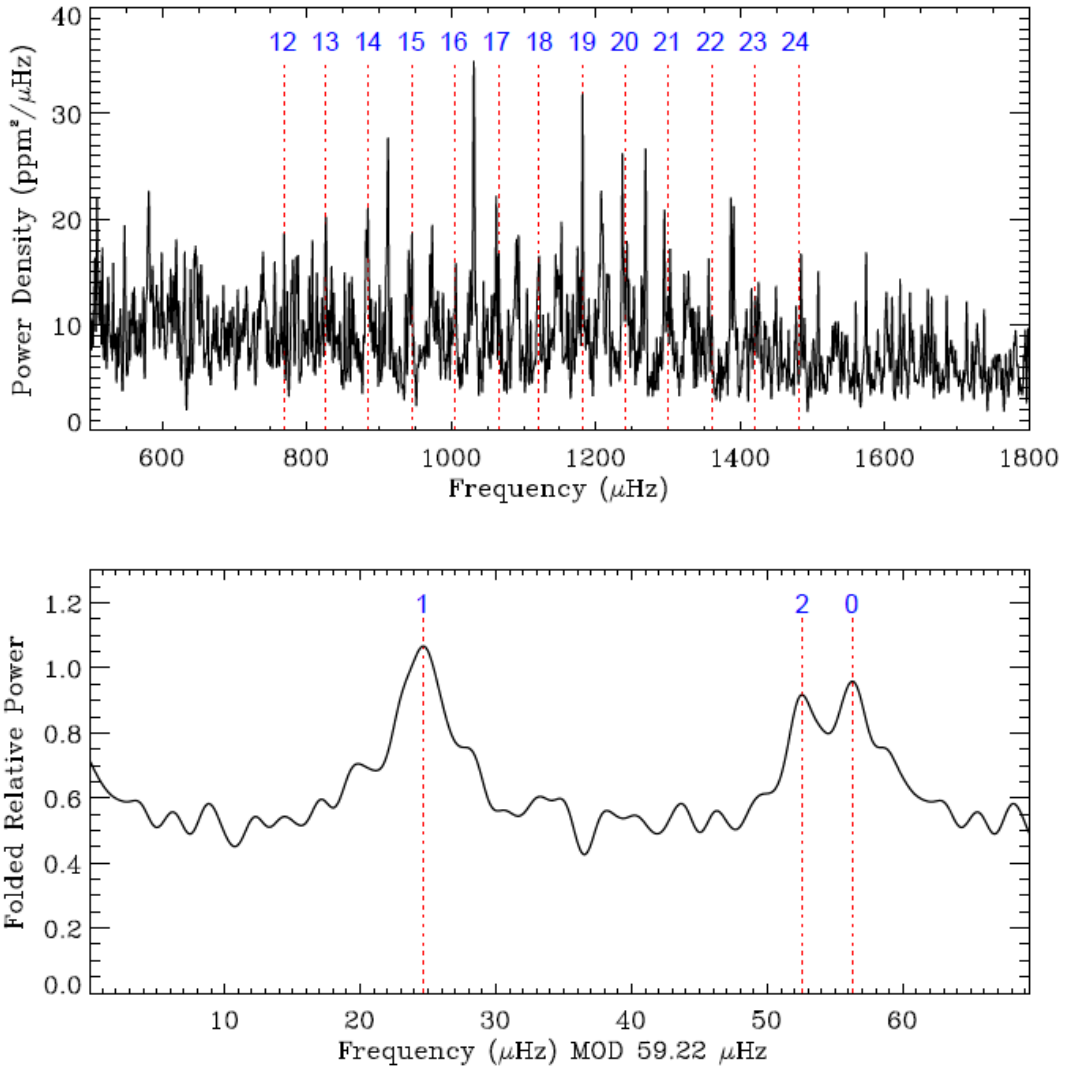
Rotation rates of stars in four open clusters in the Kepler field of view.

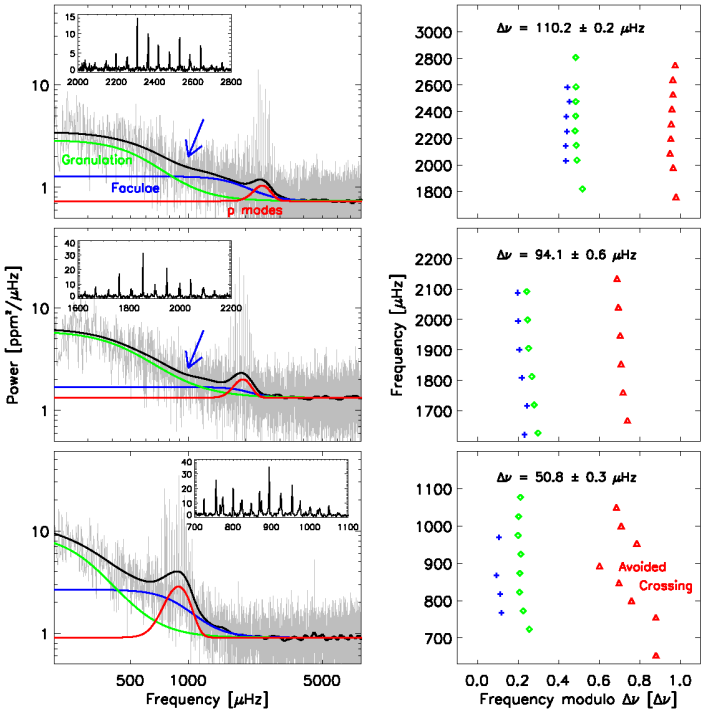
Stellar Evolution with Kepler



Color-magnitude diagram for NGC 6819. The larger points are four of the *Kepler* targets. The timescale of the oscillations increases with stellar brightness.

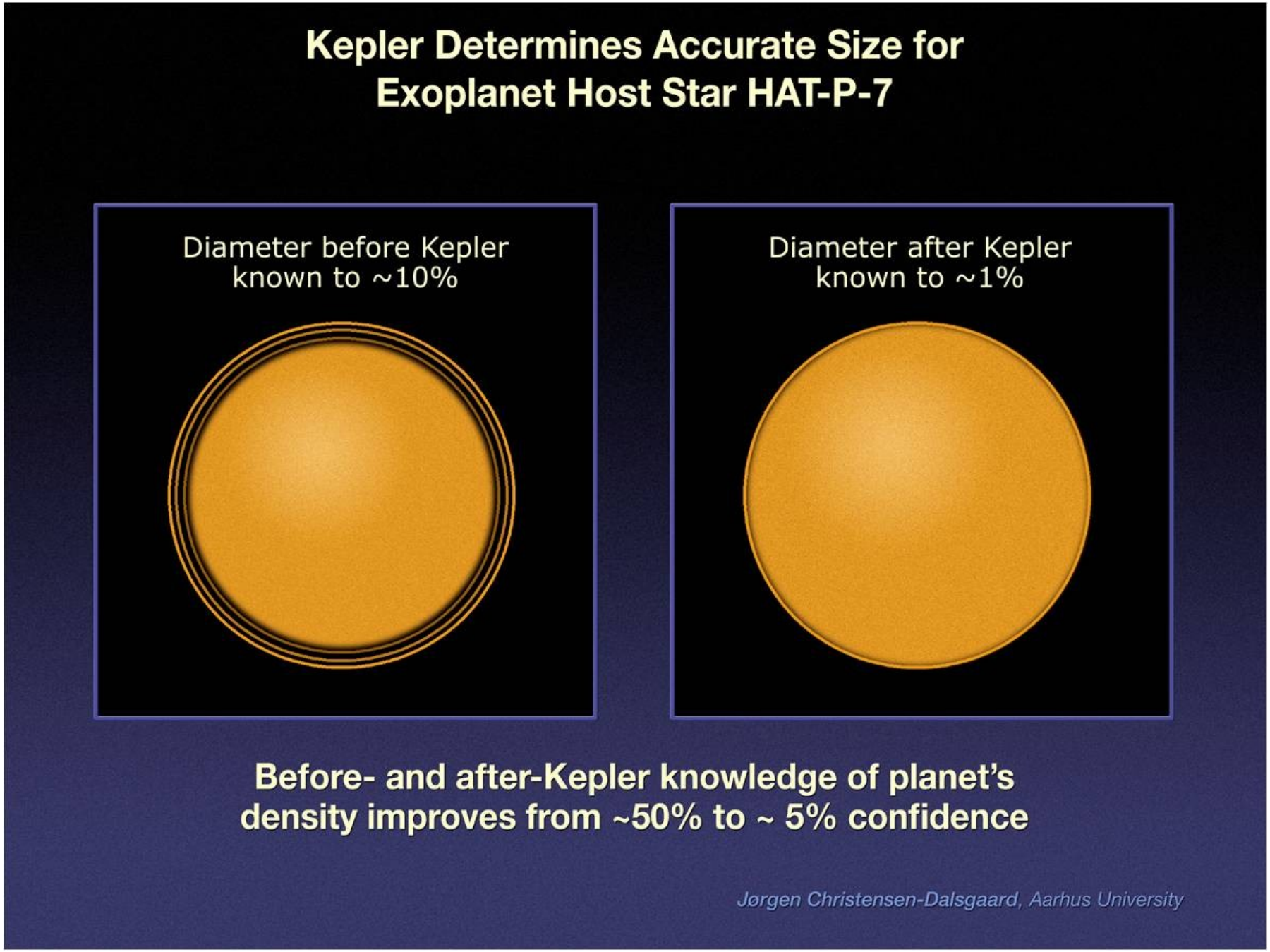
Stellar Oscillations



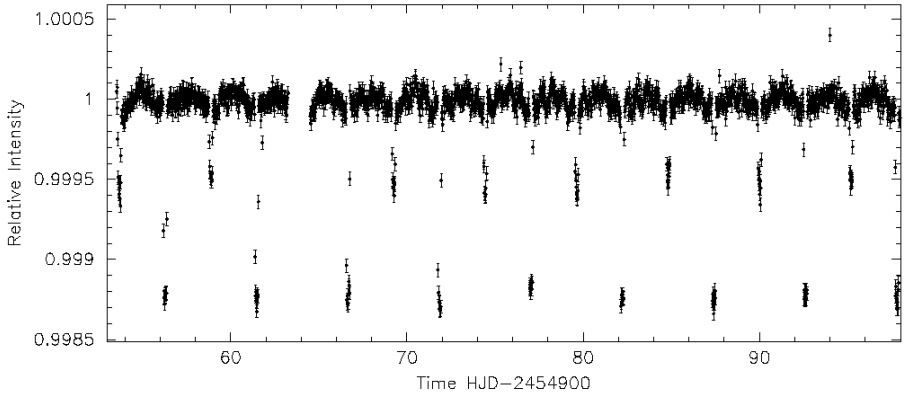


Left-hand panels: Frequency-power spectra of *Kepler* photometry of three solar-like stars (grey) over 200 – 8000 μHz.

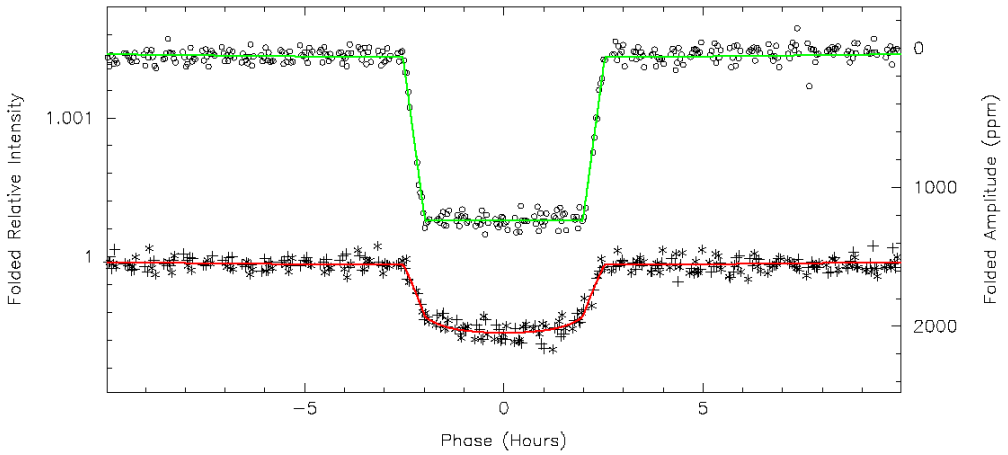
Measuring Stellar Densities



Strange Things



LIGHT CURVE



OCCULTATION: 1300 ppm

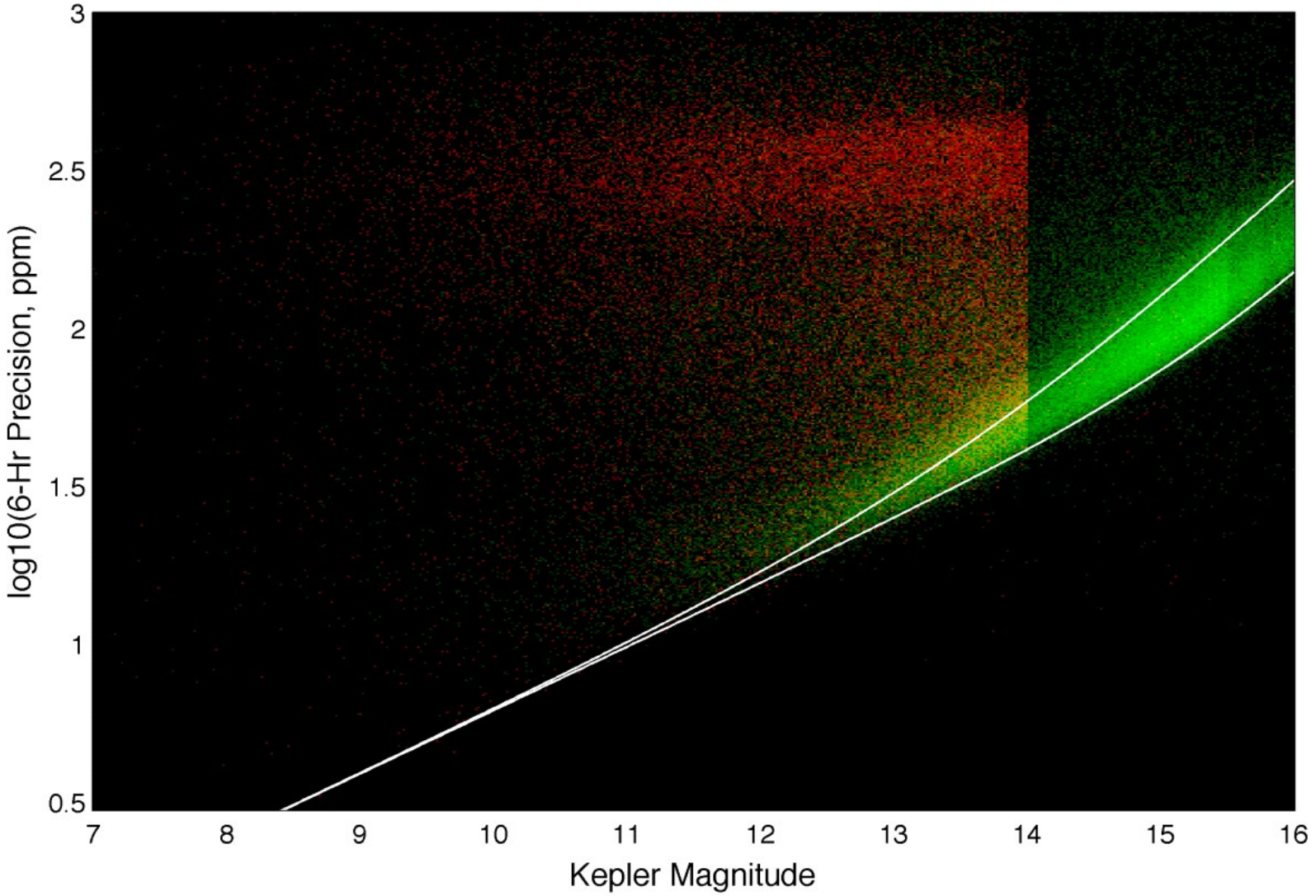
TRANSIT: 500ppm

Star temperature = 9400K
Companion temperature = 12,200K
Companion size = 0.8 R_{Jup}

Concluding Remarks

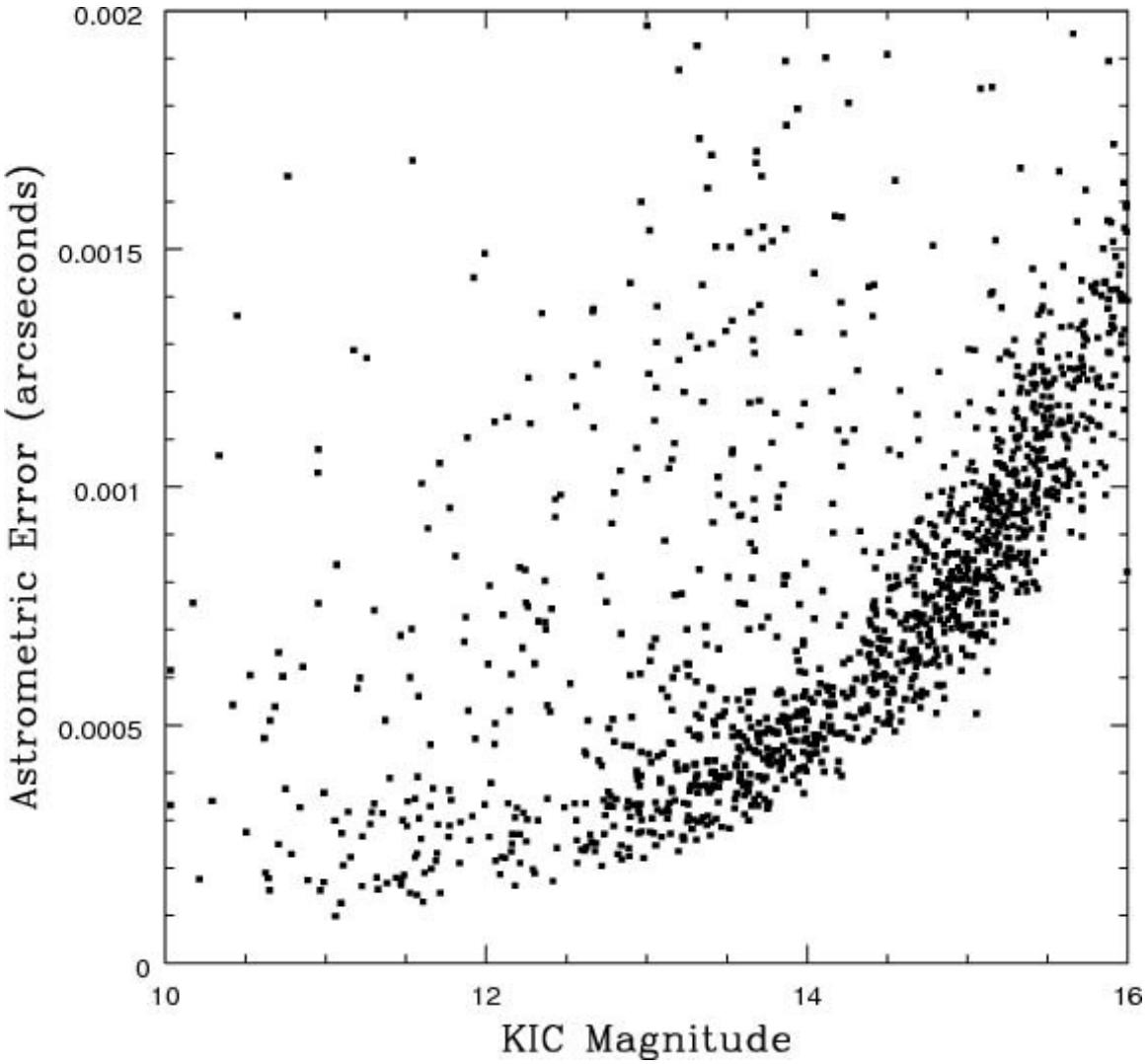
- Kepler is the first instrument capable of detecting a true Earth analog
- Kepler should answer many important questions about the population of planetary systems
- Kepler is the premier instrument for stellar variability studies
- Kepler is slated to run for 3.5 years with a possible extension to 7 – 10 years.
- A guest observer program is open to anyone to conduct non-planetary science.
- Results here are from 43 days of data, several months of data are currently available.

Special Bonus Slides



Measured 6-hour precision of the Q0 data set. A strong separation in photometric variability can be seen between the dwarfs (green points) and the red giants (red points). The two curves bound the upper and lower measurement uncertainties propagated through the data processing pipeline.

Special Bonus Slides



Astrometric error as a function of Kp magnitude for stars on Channel 2 in the Quarter 1 data collection.

Special Bonus Slides

TABLE 1
CHARACTERISTICS OF TARGET STARS

MAG	10500	9500	8500	7500	6500	5500	4500	3500	TOTAL
					$\log g \geq 3.5$				
6.50	1	0	1	2	0	1	0	0	5
7.50	1	8	9	6	8	6	0	0	38
8.50	8	20	25	24	49	15	7	8	156
9.50	9	31	81	66	116	88	11	4	406
10.50	27	37	100	209	405	359	40	9	1186
11.50	24	58	171	398	1499	1356	158	37	3701
12.50	30	44	231	676	4146	4760	626	62	10575
13.50	34	53	170	747	9279	15866	2213	157	28519
14.50	3	0	0	0	4855	29352	4227	554	38991
15.50	7	4	0	0	4449	42627	12093	1961	61141
TOTAL	144	255	788	2128	24806	94430	19375	2792	144718
					$\log g < 3.5$				
6.50	0	0	0	0	0	0	0	0	0
7.50	0	0	1	1	2	2	7	0	13
8.50	0	0	1	2	2	9	80	2	96
9.50	0	0	2	15	2	27	220	1	267
10.50	1	0	5	21	7	99	452	2	587
11.50	0	0	1	25	11	186	674	2	899
12.50	0	0	1	12	14	347	1114	0	1488
13.50	0	0	0	6	5	518	1403	0	1932
14.50	0	0	0	0	0	0	0	0	0
15.50	0	0	0	0	0	0	0	0	0
TOTAL	1	0	11	82	43	1188	3950	7	5282

Smallest and brightest stars are chosen.